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PICKERING 'B' UNIT 6 MODERATOR PIPING VIBRATION STUDY

Report No 87-85-K

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ABSTRACT

An extensive vibration monitoring program was executed on the moderator piping system at Pickering NGS 'B' from the moderator heat exchangers to the shield tank penetration following the fatigue failure of both moderator inlet pipes at the penetration. The program was composed of modal analysis, vibration monitoring at operating conditions, vibroacoustic monitoring and ultrasonic flow measurements. The results of the vibration monitoring program indicated that vibration in excess of the allowable levels was present at operating conditions on the full length of the piping system tested. Complete documentation of the results of the vibration monitoring program, conclusions and recommendations for remedial work on the system are contained in the report.

job	file	date	report no.
27-243-401	825.31	May 28, 1987	87-85-K

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EXECUTIVE SUMMARY

PICKERING 'B' UNIT 6 MODERATOR PIPING VIBRATION STUDY

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Following the failure by fatigue of the moderator inlet pipes at the penetration to the shield tank at Pickering NGS 'B' Unit 6, an extensive vibration monitoring program was executed on the piping system from the moderator heat exchangers to the penetration. The program was composed of modal analysis, vibration monitoring at operating conditions, vibroacoustic monitoring and ultrasonic flow measurements. The vibration monitoring had been previously scheduled for the unit because of fatigue problems with instrument lines and supports to other ancilliary piping in the system; however, fatigue failure of the main line after a maximum of 4 years in operation caused the focus of the work to shift.

The results of the vibration monitoring program indicated that vibration levels in excess of the allowable levels were present at operating conditions on the full length of the piping system tested. The modal analysis indicated that the piping was responding at its natural frequencies to the flow induced excitation. The vibroacoustic data revealed cavitation at several points in the line.

Inspection of other units at Pickering 'B' have indicated that the problem is generic. Short term fixes to alleviate the vibration problem at the penetration and to reduce the cavitation locally have been initiated; however, further work is necessary to determine a long term solution to the problem. Recommendations for the required investigation comprise the final section of the report.

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To Mr. J.W. Free
Technical Manager
Pickering NGS 'B'

PICKERING 'B' UNIT 6 MODERATOR PIPING VIBRATION STUDY

1. INTRODUCTION

An extensive vibration measurement program was carried out at PNGS 'B', Unit 6, on the moderator piping system between the heat exchangers and the penetration of the piping in to the calandria shield tank. The measurements were requested following the cracking of the main moderator inlet pipes at the penetration as shown in Figure 1. The metallurgical inspection/1,2/ revealed that the cracks were due to fatigue failure as a result of flow induced vibration of the piping.

The moderator piping system at Pickering 'B' has had a history of high vibration since commissioning. During commissioning a vibration survey on the piping/3/ indicated that high vibration levels, well in excess of the allowable levels/4/ established for piping, existed in the area of the "16 inch Tee" (Figure 1). As a result of this early survey, a collar support was added to the piping just below the 16 inch Tee; however, the collar support was not adequate to reduce the vibration levels for a sustained period of time.

Further vibration monitoring was required on the system in 1985 following the failure of a vent line at the weld to the main pipe just downstream of a heat exchanger outlet/5/. At this time some vibration measurements were performed on the piping just below the 16 inch Tee. The measurements revealed that excessively high vibration levels were still present at that location.

On the moderator piping system upstream of the heat exchangers, concerns had been repeatedly raised/6,7,8,9,10/ about the structural resonances of the piping at 7 Hz and 12 Hz measured on the pumpsets and a dominant mode of approximately 30 Hz, the pump running speed, measured on the piping downstream of the pumps/3/.

Recently observed fretting of a by-pass line on its support just upstream of the orifice plate on the main inlet line led to the plans to perform an extensive vibration measurement program on the moderator system during the fall outages on Units 5 and 6 in 1986. When the leak occurred in Unit 6 the plans were focussed on the Unit 6 system between the heat exchangers and the penetrations.

The vibration monitoring program objectives were to characterize the modes of vibration of the inlet piping, document the response of the piping to operating flow conditions and accurately determine the flow rates. To achieve the objectives modal analysis, vibration monitoring at operating conditions , vibroacoustic monitoring and ultrasonic flow measurements were executed.

The results of the program and recommendations for further work to aid in the determination of a long term solution to the problem are presented in the report.

2. MONITORING PROCEDURE AND INSTRUMENTATION

2.1 Vibration Measurements and Modal Analysis

The modal analysis and "running" vibration measurements were made at 22 positions along the length of the inlet moderator piping as shown in Figure 1. (The term 'running' vibration measurements defines the conditions under which the moderator pumps are in operation but the unit itself is shut down.) The measurements were made at each location with three Endevco 5241 accelerometers mounted in a triaxial configuration on an aluminum block. Because the moderator piping is 304 stainless steel, the blocks had to be attached to the piping using two worm gear ring clamps per block. The accelerometer mounting method is shown in Figure 2. Two sets of triax blocks were used to enable recording of the vibration at two points simultaneously.

The signal conditioning equipment used to record the vibration signals in velocity is shown in Figure 2.

The running measurements required a slight modification to the mounting block to enable the lower frequency bending modes to be measured in the presence of high level, high frequency flow noise. For bending mode vibration the frequency range of interest is 0-150 Hz. Flow noise is a broad band phenomenon ranging up to 15 kHz. The high frequency flow noise overloaded the charge amplifiers on the input. A mechanical filter in the form of sheet rubber glued to the base of the aluminum block was used to reduce the effect of the flow noise and enable recording of the lower frequency bending modes.

The mounted resonances of the accelerometers on the rubber mounted, clamped block were in excess of 250 Hz except for the axial accelerometer (see Figure 2) whose mounted resonance was approximately 100 Hz due to a rocking mode of the block between the two clamps. All axial data was low-pass filtered at 60 Hz.

The running data were recorded with three and four moderator pumps in operation. A survey of all twenty-two locations was performed with four pumps in operation, pumps 2,3,4,5. Following the survey, vibration records were taken at positions 3 and 4 (see Figure 1) with the three-pump and four-pump configurations listed below:

Three pump:	1,2,3
	1,2,4
	1,4,5
	1,3,5
	1,3,4
Four pump:	1,2,4,5
	1,2,3,5
	1,3,4,5
	1,2,3,4

The rubber mount was not used in the modal test which was performed with all pumps shut down. The purpose of the modal test was to characterize the piping response to a broad band input in the absence of fluid forcing functions which may selectively excite the piping. The modal test was performed by impacting the piping at a fixed position with a hammer instrumented with a force transducer and monitoring the piping response at each of the 22 measurement locations. The impact point was fixed at position 9, approximately 1 foot above the floor. (The requirement for access to stand and swing the hammer limited the choice of impact position.) Two series of impacts were carried out for each measurement location, one in the west direction and one in the south direction. Vertical impacts could not be executed at that location.

Eight or nine blows per direction were found to yield good coherence, >95%, in the south and west directions. Unfortunately there was insufficient transfer of energy to the vertical direction to provide coherent data to produce accurate vertical mode shapes. Modal analysis, using the mobility transfer function (velocity response/input force) was performed using a Nicolet 660B Analyzer.

2.2 Vibroacoustic Measurements

The mechanical filter for the accelerometers to enable measurement of the bending modes required that a second type of accelerometer be used to monitor the flow noise and the high frequency response of the piping. The procedure used to monitor the higher frequency vibration was the vibroacoustic technique/11/. A single B&K 4368 accelerometer was mounted on the wall of the pipe using beeswax to give a high mounted resonant frequency. The measurement locations and the equipment set-up are shown in Figure 3.

2.3 Flow Measurements

Flow measurements were taken during the running tests. An annubar in the piping on the vertical leg is used for station flow measurement; however, some uncertainties about flow rates following the installation of the new heat exchanger bundles made additional flow rate data desirable for corroboration of that from the annubar. A Controlotron 964 ultrasonic (transit time type) flow meter was used to measure flow rate.

Proper location of the flow meter for best accuracy posed a problem with the piping layout. For proper operation, the flow meter should be positioned at least 10 diameters downstream of any significant disturbance. The only position that fulfilled this criterion on the single line of the moderator piping was a point approximately 4 m downstream of the orifice plate on the 16" (.402 m) line as shown in Figure 3.

Prior to the work at site, the flow meter was calibrated in Design and Development Division's Flow Systems Lab (FSL) using a length of stock piping identical to that at the station/12/. The FSL loop could provide flow in the line at a maximum Reynolds number (Re) of 1.3×10^{6} which is of the same order of magnitude as 4×10^{6}, the Re of the moderator system based on the 16" diameter pipe.

During the running tests at the station, the presence of cavitation in the line downstream of the orifice caused the flow meter to operate improperly. Even at positions on the vertical leg downstream, the meter operated in a faulted condition. The best position for flow monitoring was found to be up on the 12" (0.304 m) outlet pipes from the moderator heat exchangers as shown in Figure 3. The outlet lines from both heat exchangers had to be monitored periodically to ensure an approximately 50% split in the flow between the two lines.

Upon the completion of the tests the flow meter was recalibrated in the FSL using a stock piece of 12" (0.304 m) pipe identical to that at the flow measurement location/13/. A correction factor determined by the recalibration was applied to all the flow readings.

3. RESULTS AND DISCUSSION

3.1 Running Tests

3.1.1 Vibration Measurements

The peak velocity data from the four pump survey of the twenty-two measurement locations are listed in Table 1. For typical power and process plant piping systems, including appended equipment and supports, the allowable vibration level is approximately 40 mm/s peak/4/. From the data in Table 1, it is evident that the

allowable level of 40 mm/s peak is exceeded in at least two directions at each location on the piping system. Reference 4 goes on to indicate that vibration levels in excess of 100 mm/s peak require immediate attention. At some positions on the piping the vibration level did exceed 100 mm/s peak. The peak displacement data for the four-pump operation are listed in Table 2.

The peak velocity levels listed in Table 1 represent regularly occurring peaks rather than occasional occurrences. Strip chart records of the data from positions 1 through 5 are shown in Figure 4 to illustrate the regularity of the vibration peaks.

The variation in pump combinations for four pump operation had no significant effect on the vibration levels as evidenced by the data in Table 3.

Reducing the number of pumps to three reduced the peak velocity levels by approximately 50% as shown in Table 4; however, vibration in the east and vertical directions still exceeded the allowable level of 40 mm/s peak.

The frequencies at which the piping responded to the flow-induced excitation under four-pump operation are documented in Table 5. Velocity spectra corresponding to the strip chart data in Figure 4 are shown in Figures 5(a) to 5(f) as typical examples of the spectra taken at the twenty-two locations. Dominant modes of response are at 8.75 to 9 Hz, 13 to 14 Hz, 17.5 Hz, 22.5 Hz, 25 Hz, 27.5 Hz, 32 Hz, 40 Hz, 50 Hz, 100 Hz and 105 to 106 Hz. The frequency data are indicative of a fairly broad band response to the excitation.

3.1.2 Flow Measurements

As noted in section 2.3 the flow measurements were taken on the outlet pipes for the heat exchangers. After re-calibration on the 12" (0.304 m) line the corrected flow measurements are as follows:

Four-pump operation:	1060 L/s to 1077 L/s
Three-pump operation:	910 L/s to 948 L/s.

3.1.3 Vibroacoustic Measurements

The major purpose of the vibroacoustic measurements was to monitor the high frequency content of the vibration. Implicit in such measurements is an ability to "listen" to the flow/11/.

The vibroacoustic data, taken from the positions shown in Figure 3, were played back through a stereo system to permit audio monitoring of the signal.

The audio interpretation of the signal confirmed the diagnosis of the flow meter problems on the 16" (0.402 m) line; that is cavitation was occurring at the orifice with the subsequent downstream collapse of the bubbles to produce the sharp staccato sounds characteristic of the phenomenon. The cavitation with three-pump operation was intermittent compared to the four-pump case in which the cavitation was continuous. Cavitation was also detected at the last elbow upstream of the penetration on both pipes.

The vibroacoustic data was full-wave rectified and strip chart records were made which are presented in Figure 6. The spikes which rise significantly above the background noise represent the bursts of the cavitation; for most accurate interpretation of the data, the audio analysis is also required because the background flow noise can occasionally produce spikes which do not represent cavitation. The record in Figure 6(b) of the signal from position 15 on the outlet of the heat exchanger represents a condition of low flow noise and no cavitation.

Spectra of the data both upstream of the orifice and at locations with cavitation are contained in Figures 7(a) to 7(g). By comparison of the Figure 7(a) spectrum from

position 15 where no cavitation exists and flow noise is low to that at the other positions monitored, it is evident that cavitation's major contribution is at the high frequency end of the spectrum, although there is a broadband effect as well. The small increase in the high frequency end of the spectra observed just upstream of the orifice (Figures 7(d) and 7(e) is due to an increase in flow noise although no cavitation is present.

The role of the cavitation in the vibration problem requires further investigation before detailed conclusions can be reached. Certainly the cavitation is a source of local vibration excitation caused by the rapidly fluctuating forces associated with the phenomenon/14/.

The detection of cavitation just downstream of elbows near the penetration is disturbing and begs the question of whether or not cavitation is occurring at the piping elements within the shield tank. The sections of piping removed at the penetration show evidence of wall thinning/15/ which may be the result of cavitation damage.

The pressure conditions in the system should be investigated. Pressure measurements would help to predict the extent of the cavitation and would provide information that will help to isolate the source of the vibration, that is, verify whether or not an acoustic phenomenon is driving the piping. Cavitation represents a local density change in the fluid which will affect the transmission properties of the fluid and thus contribute to or be the source of an acoustic excitation.

3.2 Modal Analysis

The resultant mode shapes from the modal analysis are documented in Figures 8(a) to 8(t), which comprise the north-south and east-west mode shapes. As discussed in section 2 the piping layout did not permit vertical impacts and the coherence of the vertical response data with the south and east hammer inputs was too low to produce accurate mode shapes.

The most accurate mode shapes, based on the spatial separation of the measurement positions, are those under 50 Hz. The data above 50 Hz is valid; however, the number of nodes between measurement positions may be underestimated and the mode shape inaccurate in detail.

The frequency data from the modal analysis are contained in Table 6. Comparison of the data from the running tests and the modal tests shows good agreement in frequency content and phase in the response to flow excitation and the hammer input; for example, the modal tests indicate a strong response at 9 Hz in the east direction that is not indicated in the north-south direction, particularly at positions on the vertical rise to the penetration, in agreement with the running data in Figure 5. The mode shape for 9 Hz, in Figure 8(a), indicates that positions 5 and 6 are in phase. The cross-spectrum of the running data from positions 5 and 6, which were recorded simultaneously, demonstrates 0 phase shift as shown in Figure 9.

The mode shapes indicate that the pipe support on the vertical rise to the penetrations is totally ineffective. This result confirms the field observation that the clamp had been pulled down at an angle from its attachment on the block wall.

The mode shapes reveal rigid body motion of the piping system from the penetrations to a point on the vertical leg just below the "Tee" at frequencies up to 23 Hz in both the north-south and the east-west directions. Above 23 Hz the mode shapes exhibit relative motion between the two legs of piping above the "Tee". Both types of motion would stress the penetration points; however, it is difficult to assess the severity of the motion with respect to the penetrations since limited access prevented measurement at those locations. It is also difficult to determine the influence of motion upstream of the penetration on the runs of piping downstream of

the penetration and vice-versa. Preliminary finite element analysis/16/ of the entire length of piping from the heat exchangers to the calandria predicts modal amplitudes of the piping in the shield tank of the same order of magnitude as those upstream of the penetration.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the results of the vibration program:

1. Excessively high vibration levels, in the range of 40 mm/s peak to 158 mm/s peak, exist on the moderator piping system downstream of the heat exchangers to the penetration to the shield tank with four pump operation. With three-pump operation the levels are reduced but at some locations the vibration still exceeds the allowable level of 40 mm/s peak.

2. Modal analysis has demonstrated that the piping system is responding under operating conditions at its natural frequencies. The modal analysis should be used to assess any proposed modifications to the piping system.

3. Cavitation was detected in the piping under four- and three-pump operating conditions at the orifice and at the last elbow upstream of the penetration on each inlet line.

4. Flow measurement with an ultrasonic flow meter produced the following results:

Four-pump operation:	1060 L/s to 1077 L/s
Three pump operation:	910 L/s to 948 L/s

The vibration program has identified the following areas of concern:

1. Source of vibration: Vibration in a piping system can be excited by any one or several of the following mechanisms:

a) The piping can respond at its natural frequency to the broad band energy input from the flow in the system;

b) Acoustic modes in the fluid can cause large amplitude vibration when they match the natural bending mode frequencies of the piping;

c) Energy may be transmitted mechanically from one structure to another which, if at one of the natural frequencies of the receiving structure, can excite large amplitude vibration.

Further measurements must be carried out to aid in the source identification.

2. Severity of vibration and cavitation in the piping within the shield tank:

The piping system from the heat exchangers to the calandria is a continuous system which implies that whatever flow induced vibration mechanism is acting on the section upstream of the penetration also acts downstream. The same reasoning applies to the cavitation at elbows and other piping elements. With the present body of information the condition of the piping within the shield tank cannot be assessed.

The following recommendations have been proposed to address the areas of concern:

1. A program of dynamic pressure and vibration measurements should be carried out on the accessible sections of the system to determine whether or not an acoustic/structural interaction is present in the system. Static pressure measurements made at the same time would provide the data necessary to define the extent of the cavitation problem.

2. Vibration measurements should be carried out on the piping within the shield tank. These measurements should include techniques for detection of cavitation. Appropriate instrumentation development should be carried out to achieve these measurements. Measurement of the piping vibration in the shield tank is the only sure way to determine if there is a problem downstream of the penetrations and whether modifications remedy it.

3. Consideration should be given to full-scale model testing of the moderator system from the heat exchangers to the calandria. Such a model could be built and operated at the Nuclear Process Components Test Facility at Research Division. A proposal outlining the program is included as Appendix A.

The full-scale model would permit evaluation of the efficacy of modifications to the piping system without costly station outages. The model tests would be interpreted with respect to the field measurements to ensure the validity of the model data.

4. A vibration measurement program similar to that just completed on the moderator inlet lines should be carried out on the moderator drain lines. Previous work on the pumps/6,7,8,9,10/ has suggested a possible structural resonance of the piping at the pump running speed.

ACKNOWLEDGEMENTS

The vibration measurements at site were carried out by G. Bakker, J.W. Forest, P. Hoogendam and M. de Montmorency. The ultransonic flow meter used was the property of Utilization Section, Electrical Research Department. F. Lenarduzzi and R. Ruch were very helpful with the loan of the equipment.

The flow meter calibration was carried out by the staff of Flow Systems Laboratory, Design & Development Division.

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TABLE 1: PICKERING 'B' UNIT 6 MODERATOR PIPING VIBRATION SURVEY

FOUR PUMP SURVEY

	VELOCITY IN mm/s peak		
	east	*south*	*vertical*
Location			
1	60	3.2	70
2	64	1.6	70
3	95	88	76
4	90	66	60
5	88.5	90	44
6	85	95	51
7	95	70	25
8	107	70	38
9	100	90	40
10	60	9	158
11	50	8	95
12	50	8	90
13	50	7	80
14	70	12	74
15	50	50	40
16	88	64	40
17	50	50	40
18	80	70	40
19	50	50	36
20	76	50	40
21	45	50	14
22	50	40	20

TABLE 2:PICKERING 'B' MODERATOR PIPING PEAK DISPLACEMENT MEASUREMENTS

FOUR PUMP SURVEY

PEAK DISPLACEMENT IN μM

LOCATION	*EAST*	*SOUTH*	*VERTICAL*
1	160	20	240
2	160	10	240
3	300	100	300
4	280	100	450
5	350	290	300
6	240	300	350
7	300	160	300
8	400	160	300
9	260	160	250
10	120	50	380
11	140	30	110
12	110	30	230
13	130	30	150
14	170	40	150
15	150	280	280
16	250	350	250
17	200	230	280
18	220	250	250
19	230	230	300
20	300	250	250
21	130	200	100
22	160	250	80

TABLE 3: FOUR PUMP COMBINATIONS:COMPARISON OF PEAK VELOCITIES at LOCATIONS 3 & 4

VELOCITIES IN MM/S PEAK

	EAST 3/4	*SOUTH 3/4*	*VERTICAL 3/4*
PUMPS			
1,2,4,5	120/100	100/68	96/63
1,2,3,5	112/110	96/60	88/57
1,3,4,5	124/100	100/60	84/57
1,2,3,4	104/88	100/56	80/54
2,3,4,5	95/90	88/56	76/60

TABLE 4: THREE PUMP COMBINATIONS:COMPARISON OF PEAK VELOCITIES at LOCATIONS 3 & 4

VELOCITIES IN MM/S PEAK

	EAST 3/4	*SOUTH 3/4*	*VERTICAL 3/4*
PUMPS			
1,2,3	48/49	37/31	72/56
1,2,4	52/56	46/33	68/46
1,4,5	56/48	49/31	64/48
1,3,5	50/56	47/37	64/46
1,3,4	48/56	47/35	70/48

TABLE 5 a: EAST DIRECTION FREQUENCY DATA FROM FOUR PUMP OPERATION

*Frequencies in Hz; dominant frequencies: **

location	
1	22.5*, 25*
2	22.5*, 25
3	22.5*, 25*, 100*
4	22.5*, 25*, 100*, 105
5	8.75, 22.5, 27.5*, 50, 100
6	8.75, 27.5*, 50*, 105*, 155
7	8.75*, 32.2, 39
8	8.75*, 32.2, 39, 107.5*
9	9, 28, 32.5*, 39, 106.3*, 125
10	28*
11	14*, 28*, 32
12	14, 33*, 40
13	13*, 17.5, 22
14	9, 13, 17.5*
15	13.75*, 20
16	9, 17.5*
17	12.5, 17.5*, 40
18	17.5*, 40*
19	13.5, 17.5*, 40
20	13.5, 17.5*, 40
21	13.5, 17.5*
22	13.5, 17.5*

TABLE 5 b: SOUTH DIRECTION FREQUENCY DATA FROM FOUR PUMP OPERATION

*Frequencies in Hz; dominant frequencies: **

location	
1	13.5, 25, 96.5*
2	22.5, 30.25, 38.5, 35.25, 91.5*
3	13.5, 40, 50, 73.4, 100*
4	13.5, 28*, 40
5	13.5, 25.6*, 28*
6	28*
7	13.5*, 22.5*, 28*
8	13.5*, 22.5, 28, 40*
9	13.5, 25, 27.75, 40*, 73.5
10	13.5, 25, 50.5, 82.25, 91.5*
11	13.0, 24.75, 56.5, 76*
12	18, 24.75, 73.75*
13	13.5, 25.5, 73.5*
14	13.25, 25.5, 73.25*
15	12*
16	9.2*, 12, 17.4
17	12*, 17.4, 40
18	9*, 12*, 17.4*, 40
19	13, 17.4*, 20, 28, 40
20	13*, 20, 40
21	11.5, 13.5, 17*, 25.25, 35.75
22	13.5, 17.25*, 30.5, 37.5

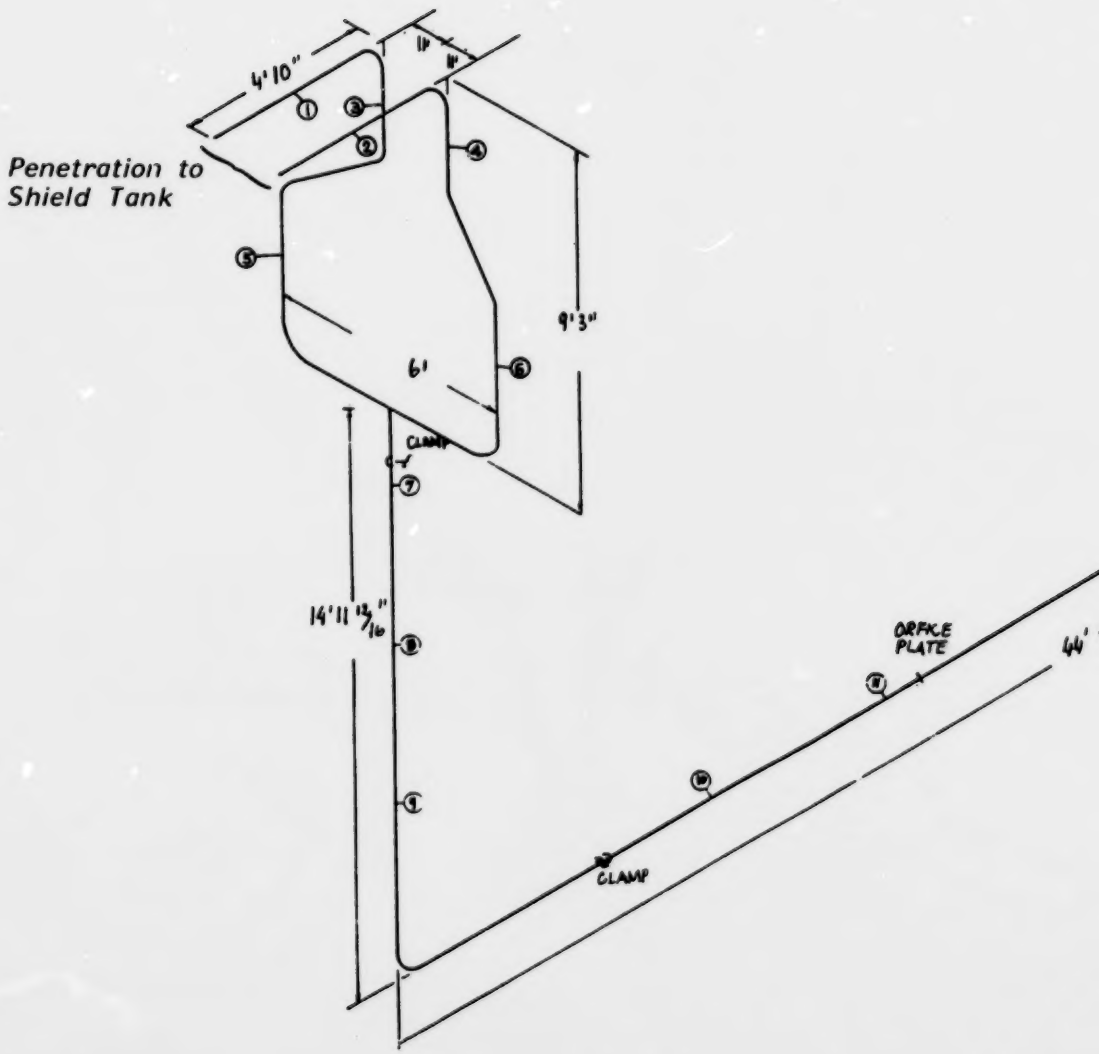
TABLE 5 c: VERTICAL DIRECTION FREQUENCY DATA FROM FOUR PUMP OPERATION

*Frequencies in Hz; dominant frequencies: **

location	
1	13.75, 27.5*, 38.75*, 50, 100
2	13.75*, 27.5*, 38.75, 50, 100
3	13.75*, 26*, 38.5, 50.5, 101, 105, 108.5, 135.5
4	13.75*, 28*, 33.5, 38
5	13.5*, 25*, 38.5
6	13.5*, 25*, 38.5
7	13.5*, 25*
8	13.5*, 25
9	13.6*, 17.6
10	13.6*, 17.6, 125*
11	13.5*, 18*, 25
12	13.5*, 18*, 25
13	20*, 100
14	17.5*, 33.5, 100
15	8, 11.5, 17.5*, 25, 39.5
16	9, 11.5, 13.5, 17.5*, 39.5
17	11.75*, 17.75*, 40, 8.75
18	9, 11, 12.5*, 17.5*, 34.5, 40, 81.75
19	11.5, 17.75*, 36.2, 39.5, 77
20	9, 11.5, 12.75, 17.5*, 32.75, 39.5, 80.25
21	12.5, 14.3, 17.3, 45.3, 53.75, 92.5*
22	13, 17.5, 39.8, 45.5, 53.3, 80.5*

TABLE 6: MODAL FREQUENCIES

	frequencies in Hz	
	EAST	*SOUTH*
mode		
1	9.0	13.0
2	15.0	16.5
3	16.5	23.0
4	19	40.5
5	24.5	65
6	26.5	68
7	77	74.5
8	101	103.5
9	104	105.5
10	105.5	106.5
11	106.5	124.5
12	127	127.5
13	135.5	129.5
14	142	135.5


4'10"
1"
4"
Penetration to
Shield Tank
9'3"
6'
CLAMP
14'11 13/16"
ORIFICE
PLATE
44'
CLAMP

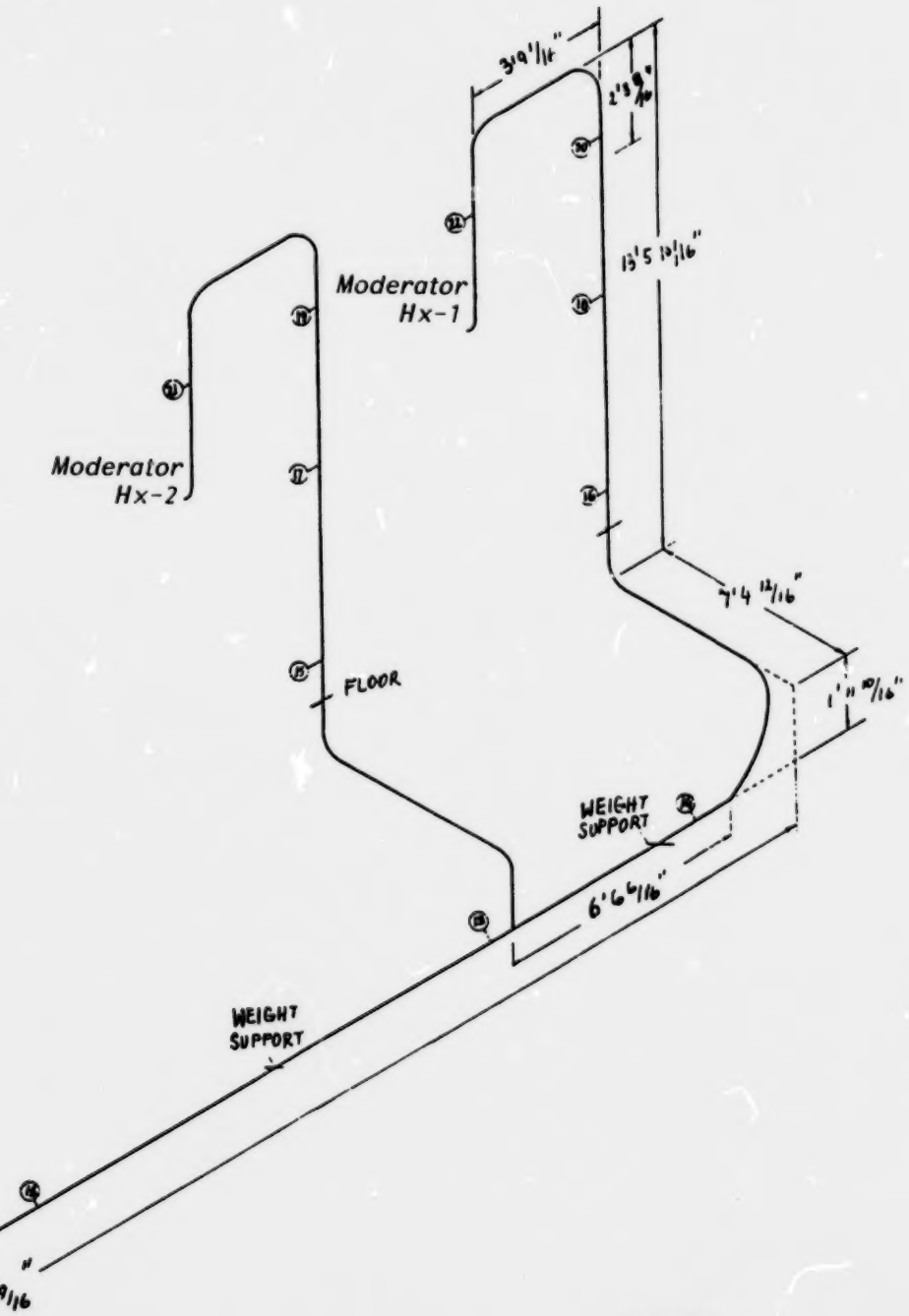


FIGURE 1

PIPING LAYOUT AND MEASUREMENT LOCATIONS

200773-RD

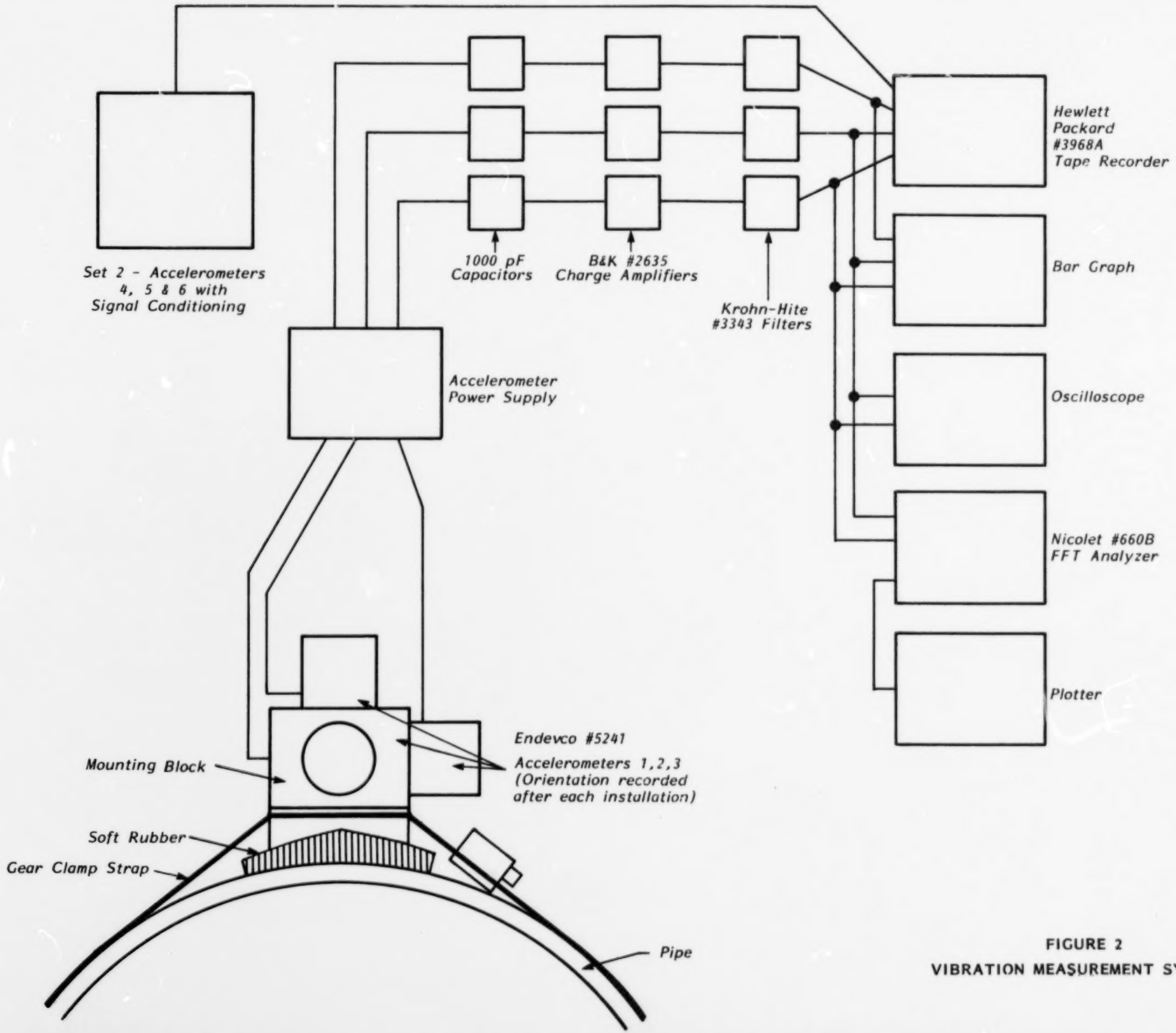


FIGURE 2
VIBRATION MEASUREMENT SYSTEM

200774-RD

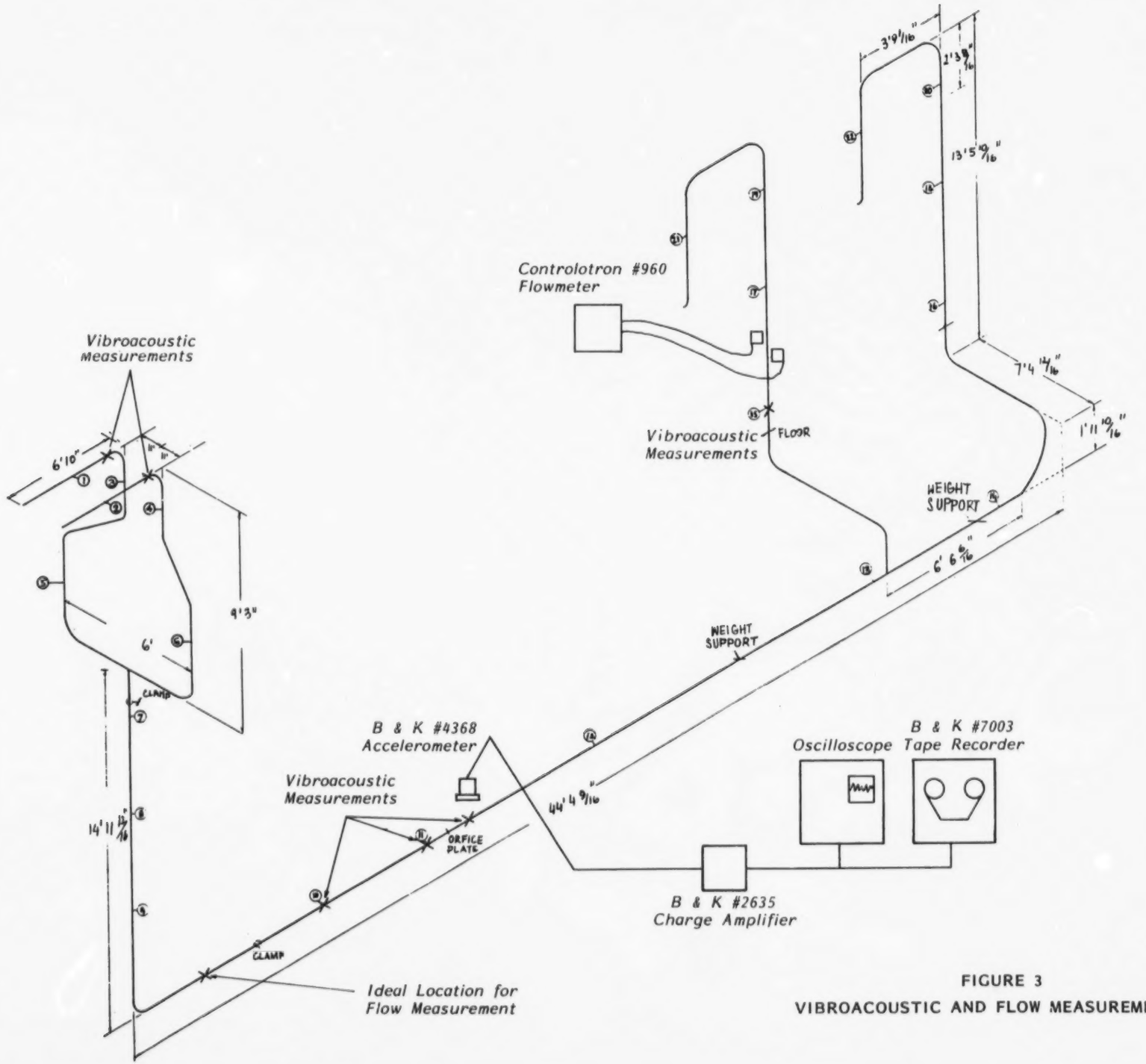


FIGURE 3
VIBROACOUSTIC AND FLOW MEASUREMENTS

200775-RD

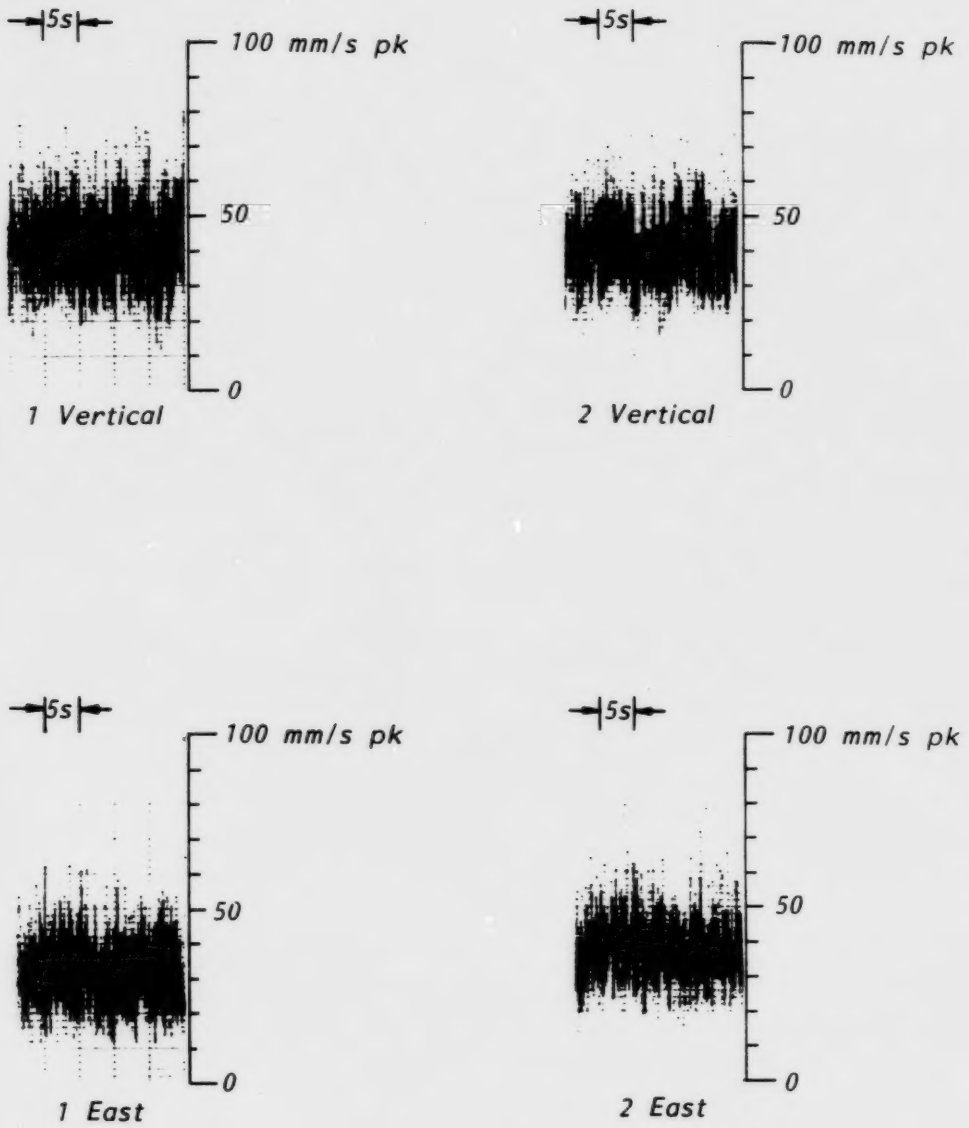
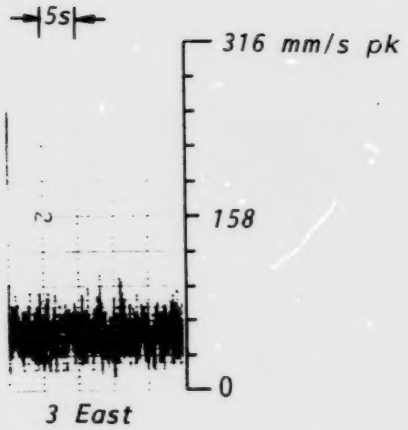
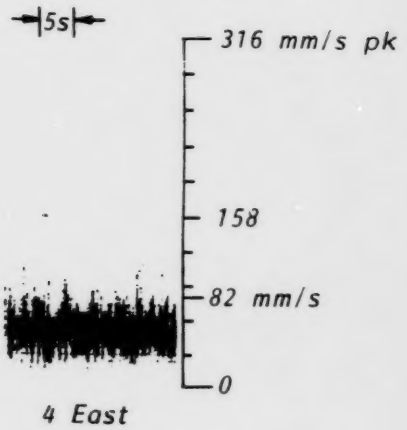
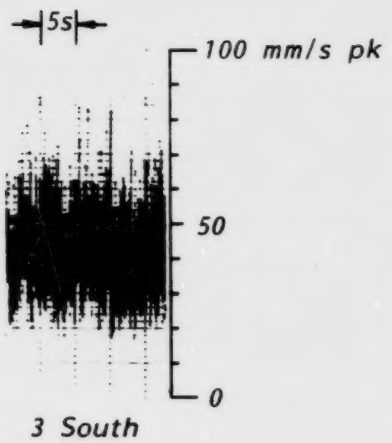


FIGURE 4
PEAK VELOCITY DATA IN mm/s FOR 4-PUMP SURVEY

174118-RD







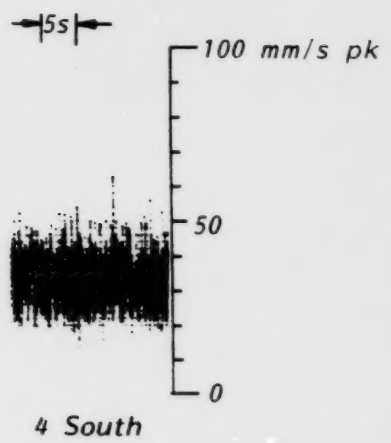
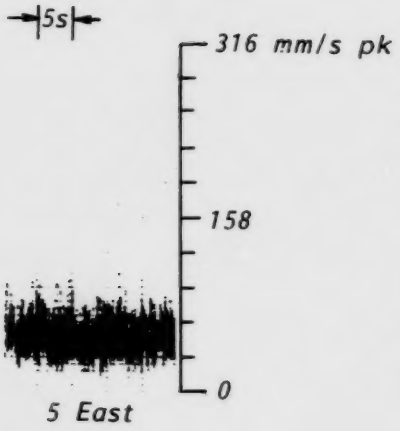
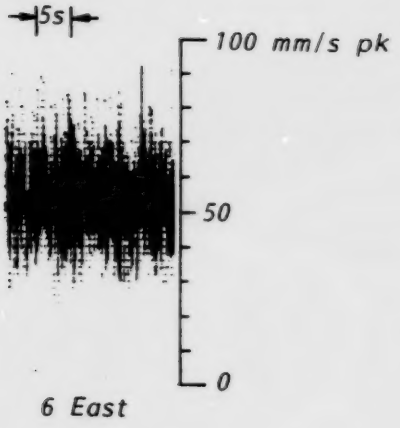
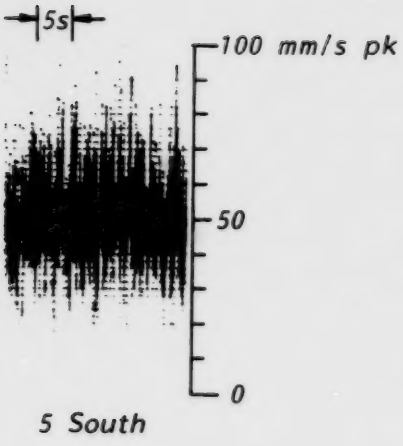


FIGURE 4
CONT'D







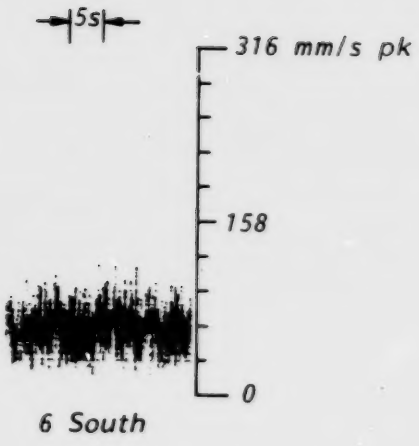


FIGURE 4
CONT'D

174127-RD

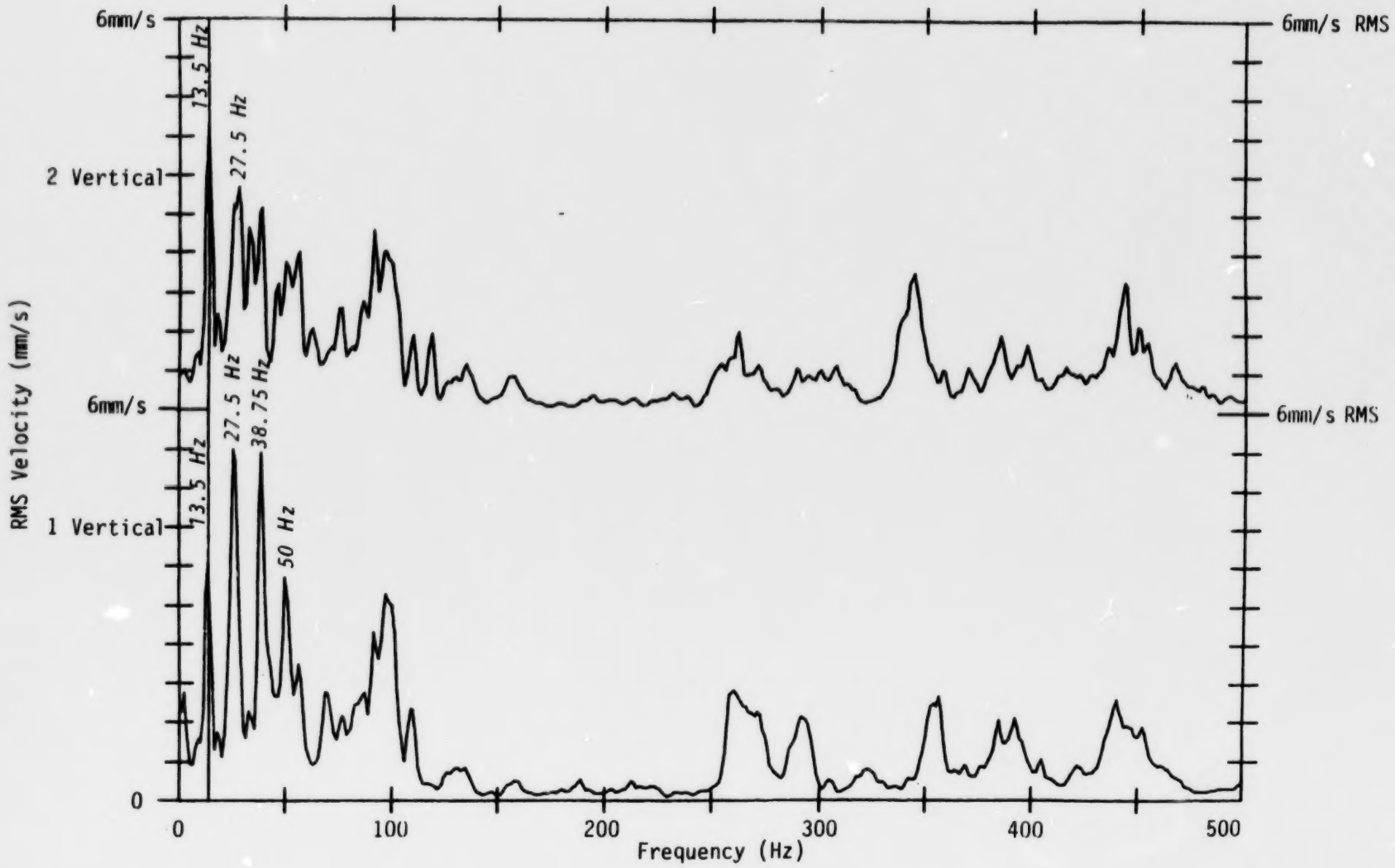


FIGURE 5 (a)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 2-VERTICAL
CHANNEL B: 1-VERTICAL

174130-RD

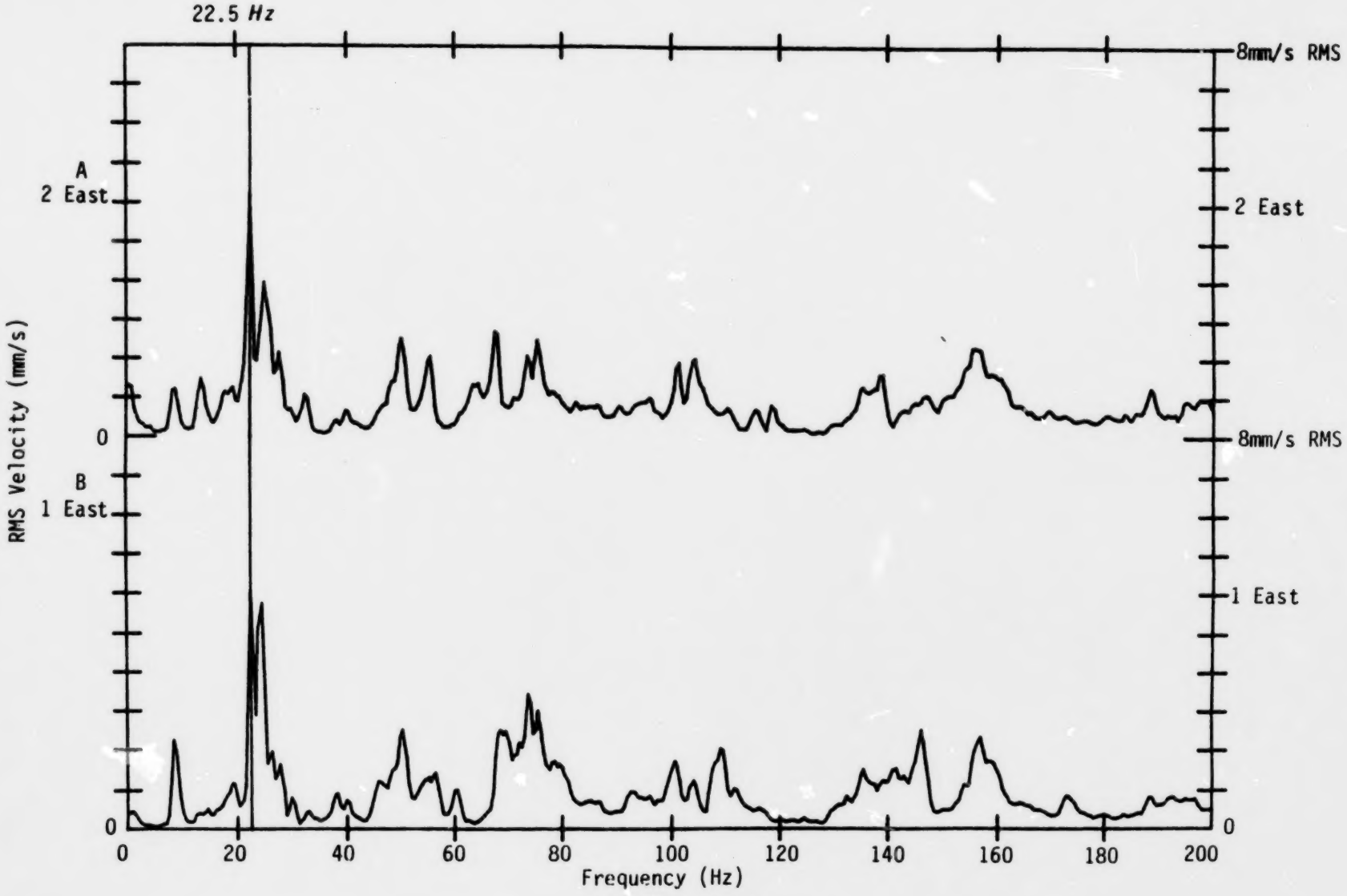


FIGURE 5 (b)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 2 EAST
CHANNEL B: 1 EAST

174131-RD

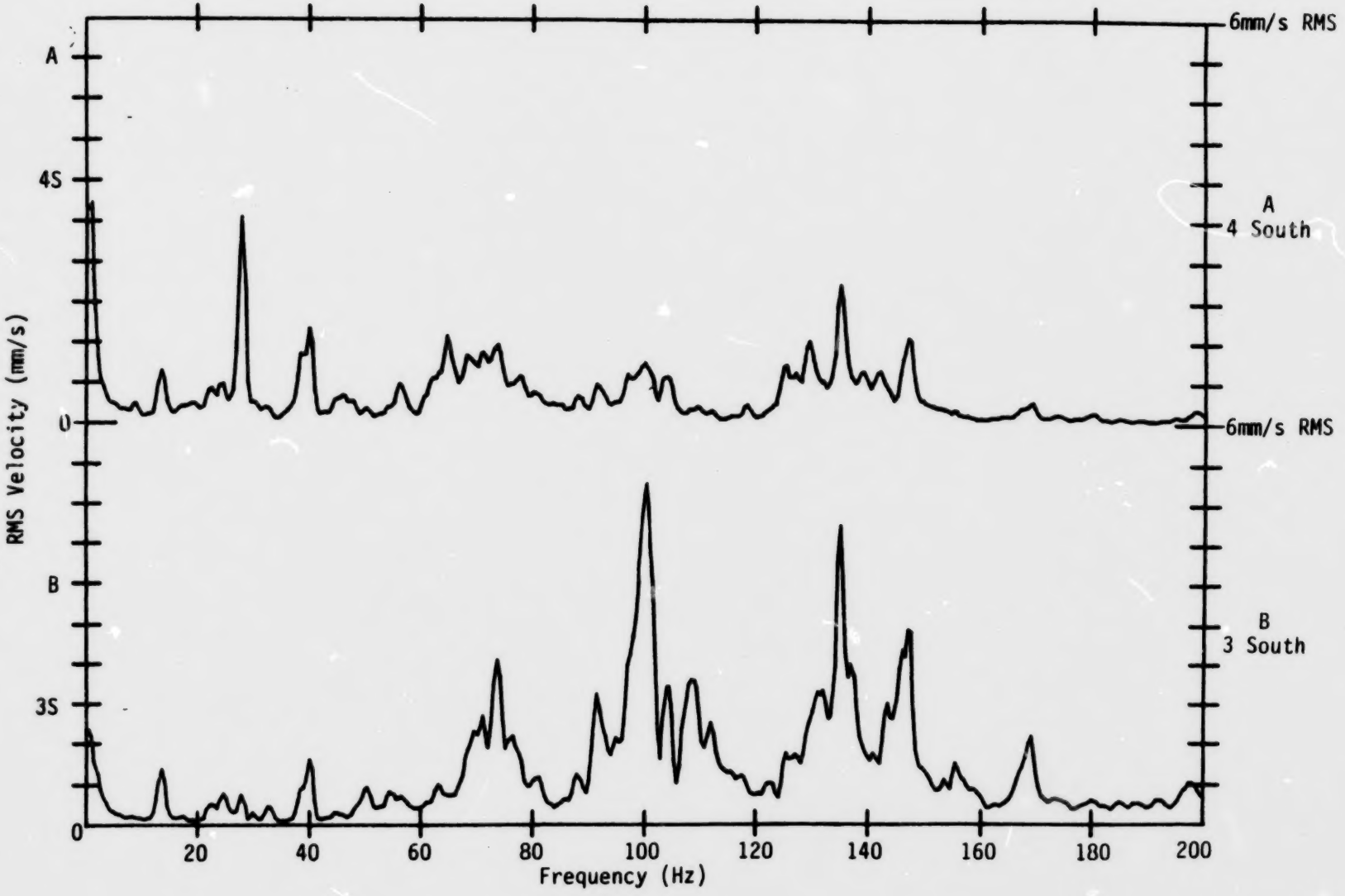


FIGURE 5 (c)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 4S
CHANNEL B: 3S

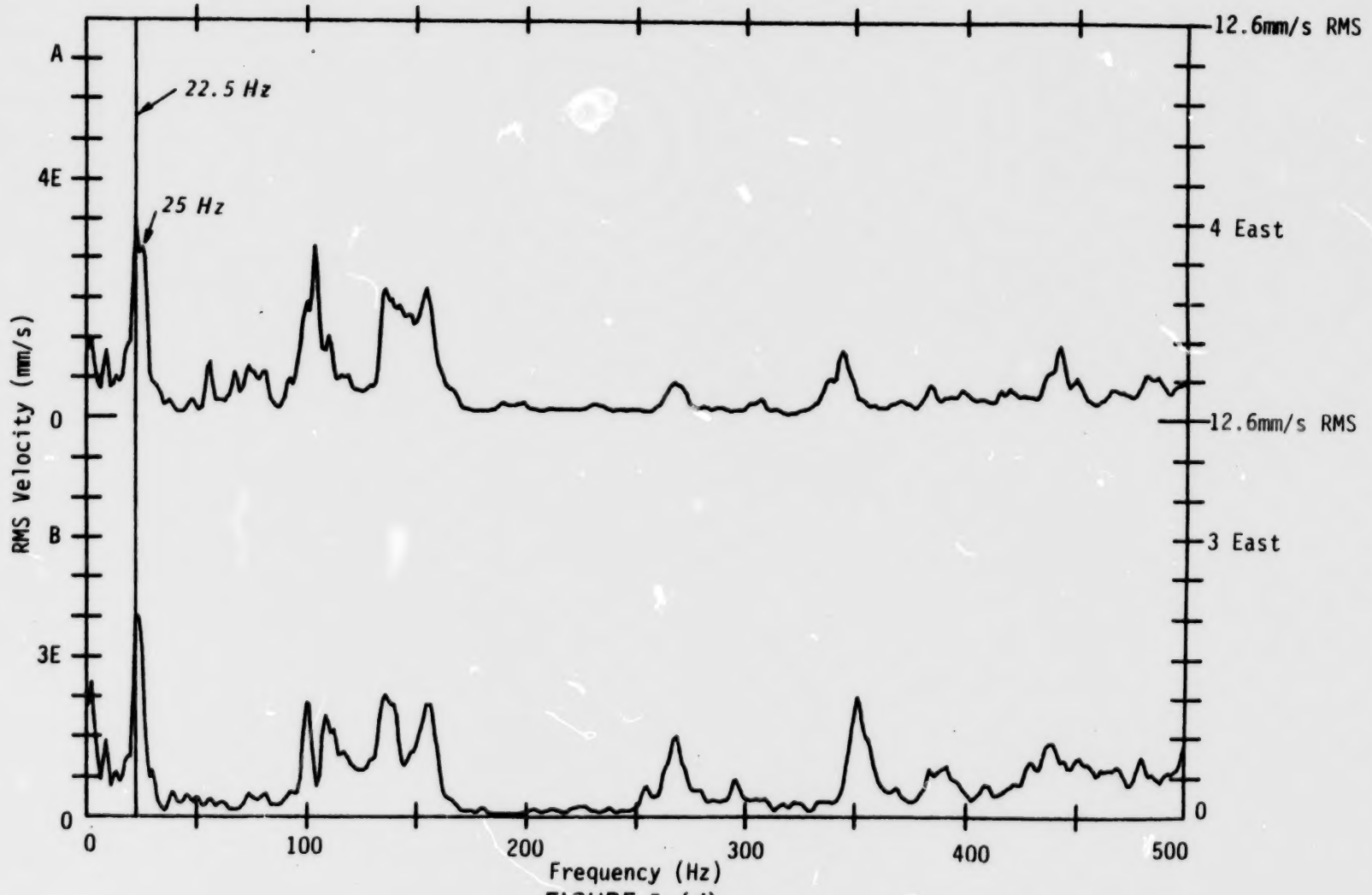


FIGURE 5 (d)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 4 EAST
CHANNEL B: 3 EAST

174163-RD

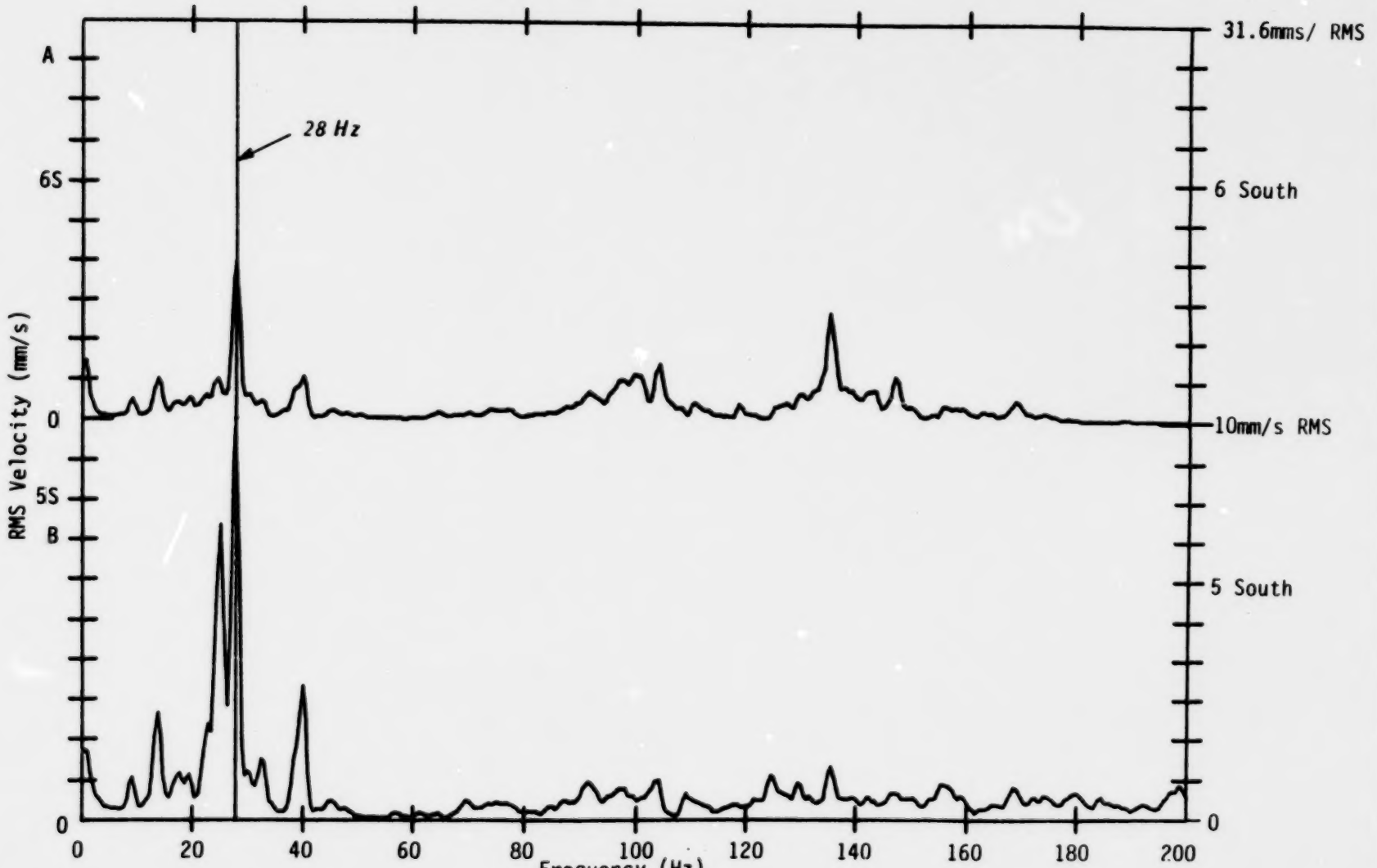


FIGURE 5 (e)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 6 SOUTH
CHANNEL B: 5 SOUTH

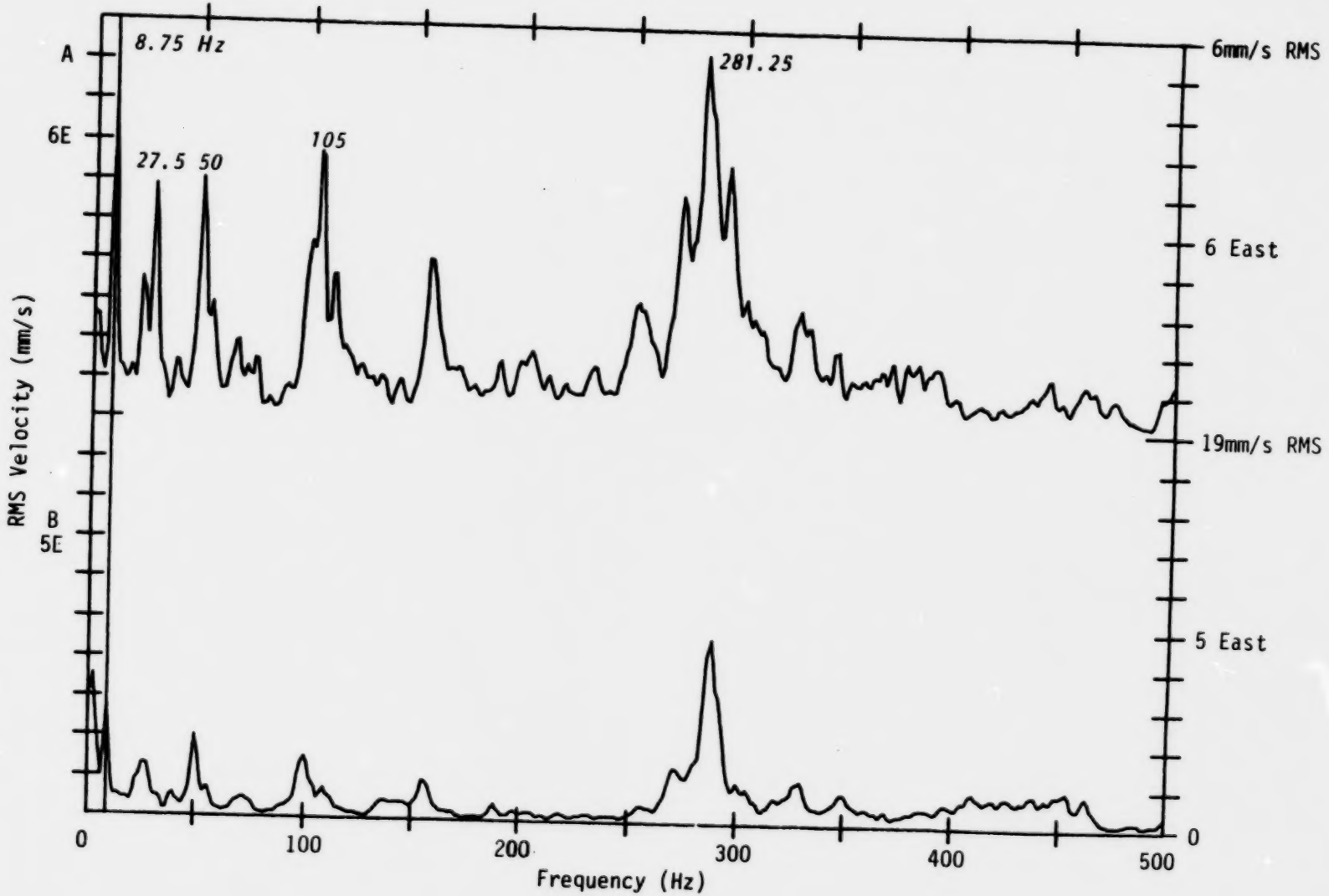


FIGURE 5 (f)

RMS SPECTRA FROM 4-PUMP SURVEY
CHANNEL A: 6 EAST
CHANNEL B: 5 EAST

174141-RD

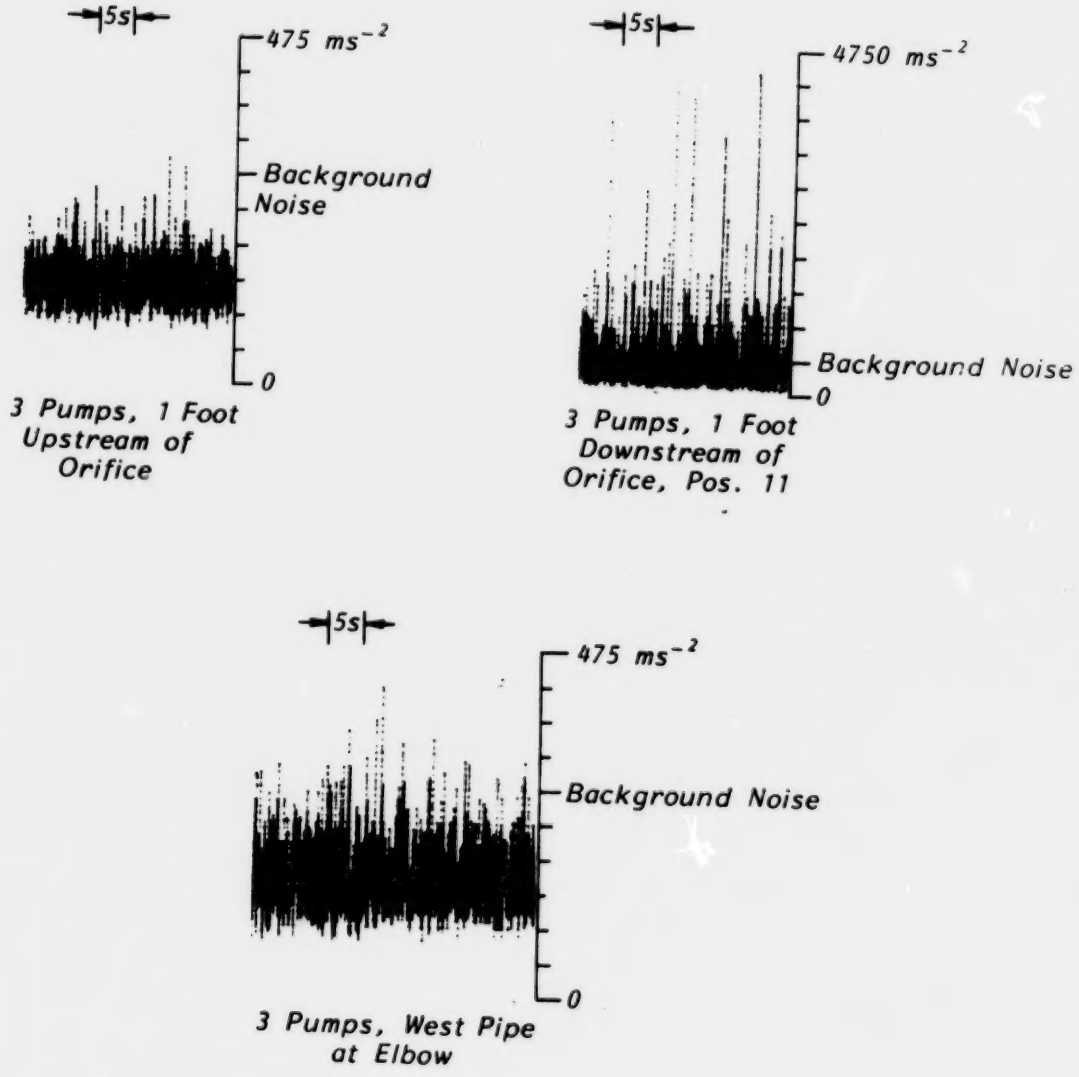


FIGURE 6 (a)

VIBRO ACOUSTIC DATA WITH 3 PUMPS OPERATING (FULL-WAVE RECTIFIED DATA)

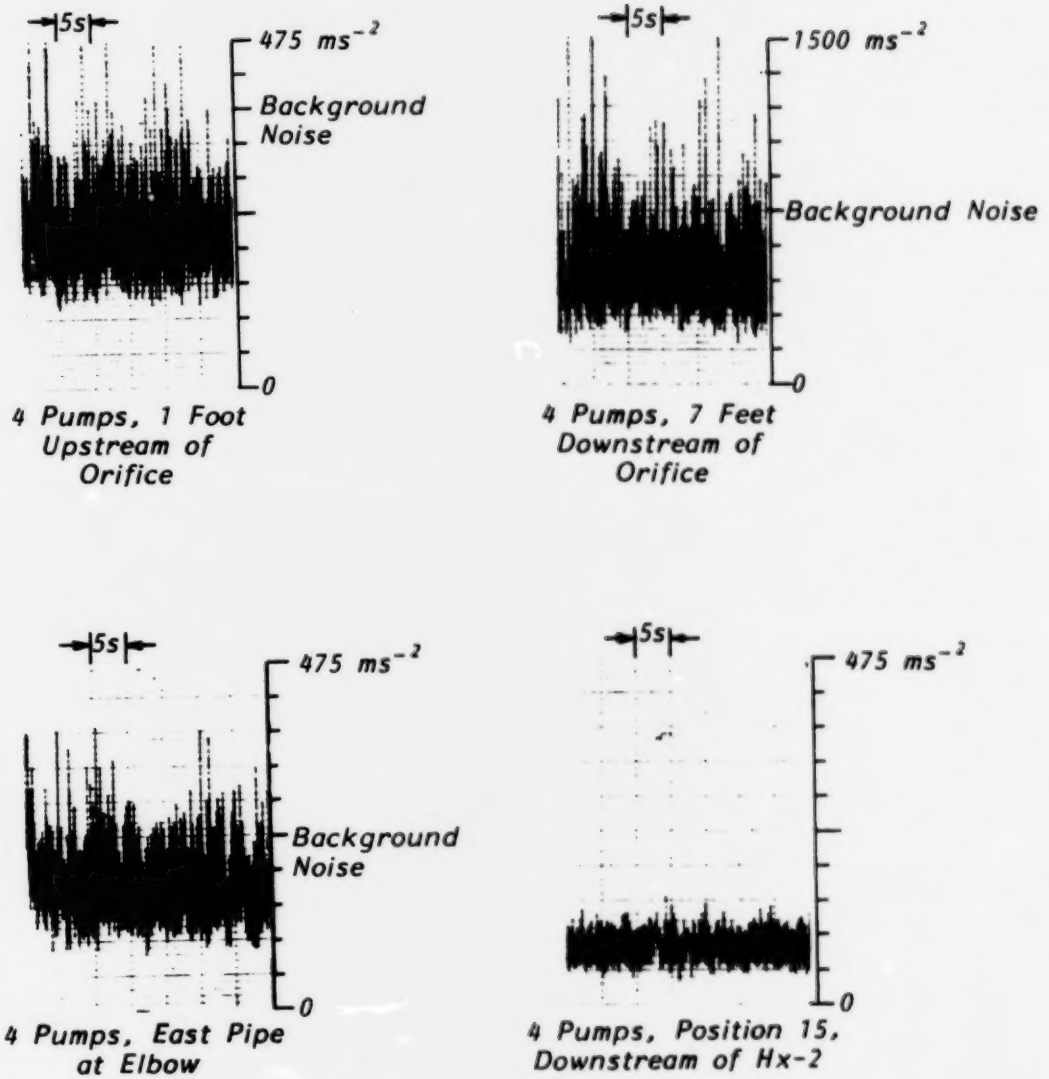


FIGURE 6 (b)

VIBRO ACOUSTIC DATA WITH 4 PUMPS OPERATING (FULL-WAVE RECTIFIED DATA)

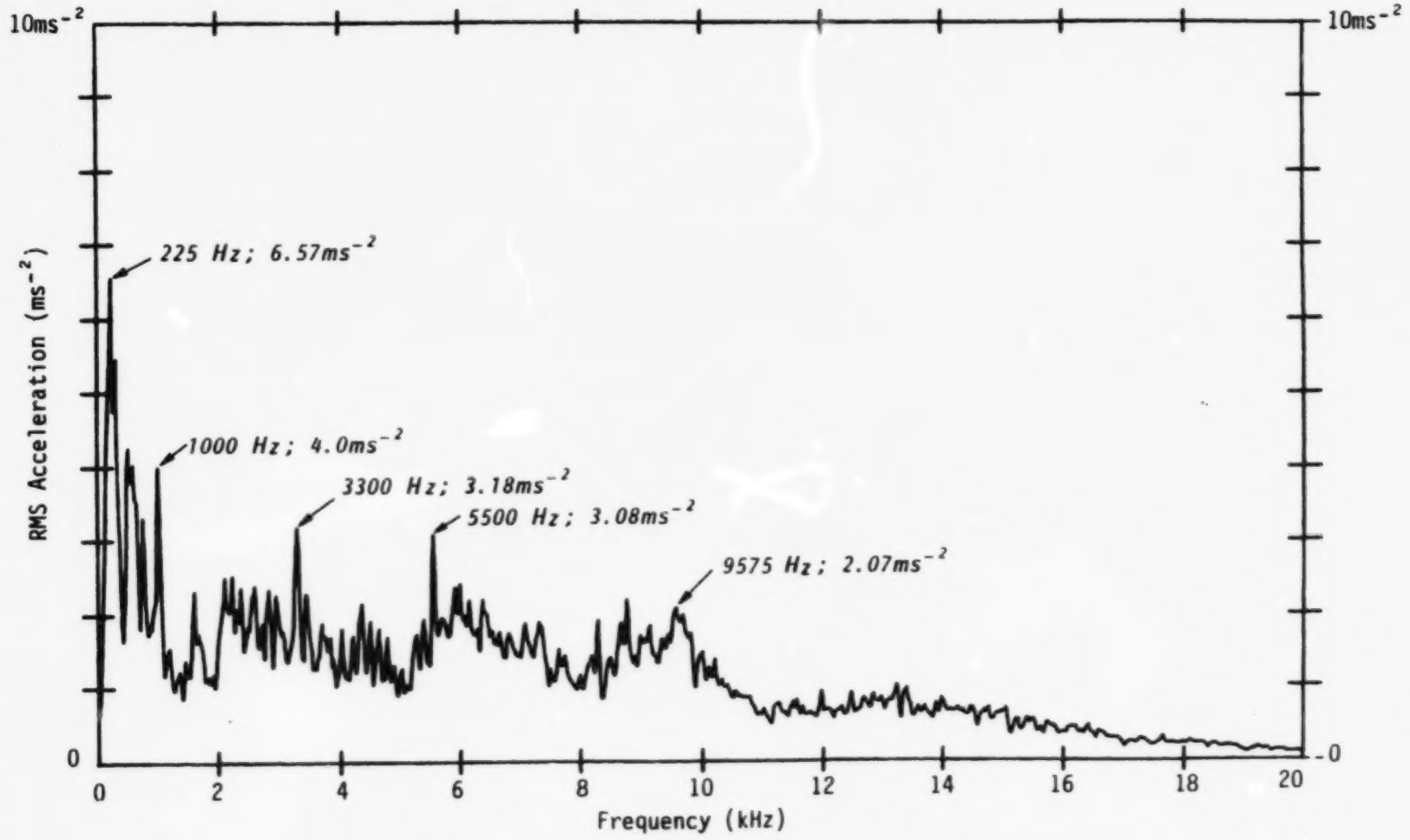


FIGURE 7 (a)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 4-PUMP OPERATION
OUTLET OF HX (POS. 15)

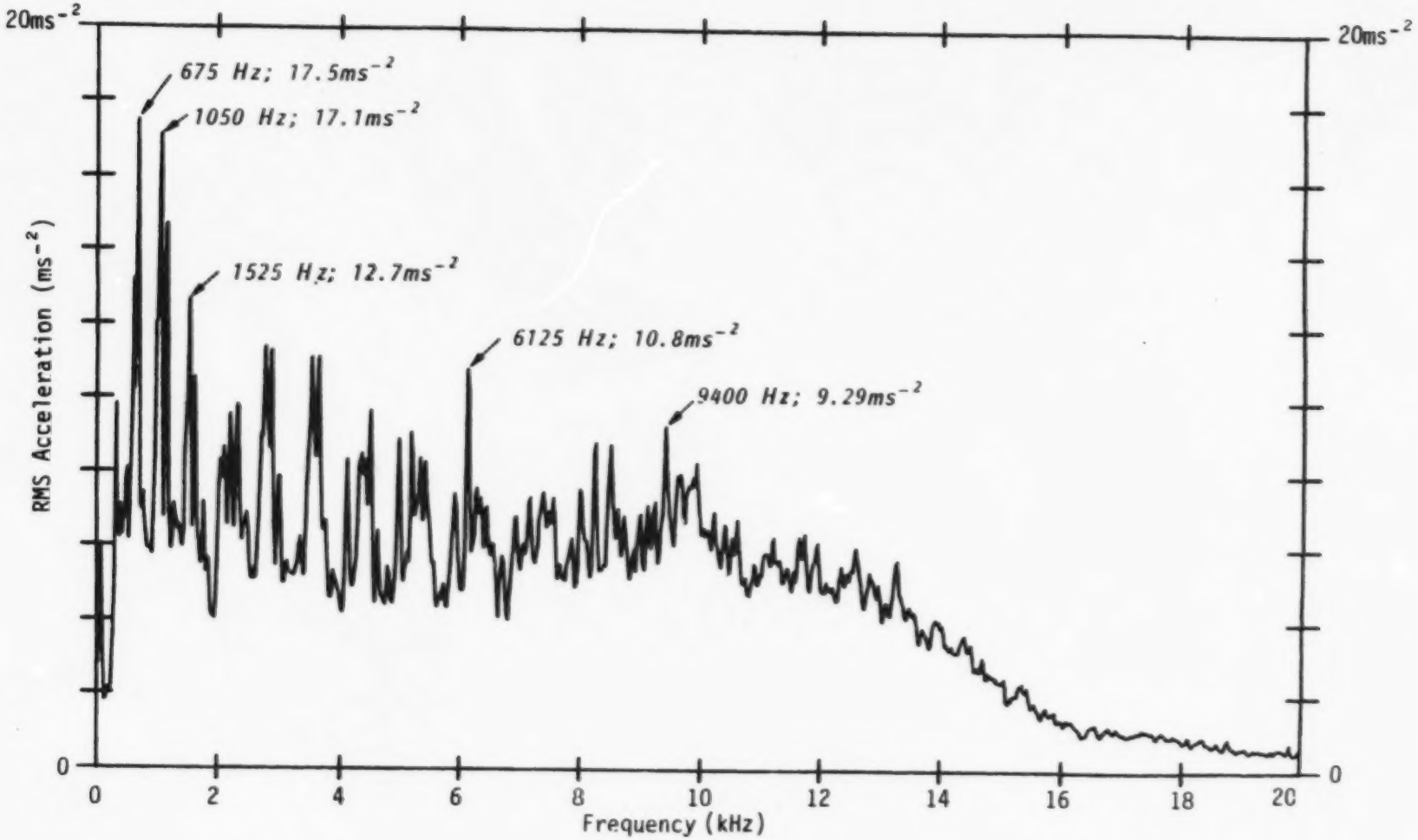


FIGURE 7 (b)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 3-PUMP OPERATION
DOWNSTREAM OF ORIFICE (POS. 11)

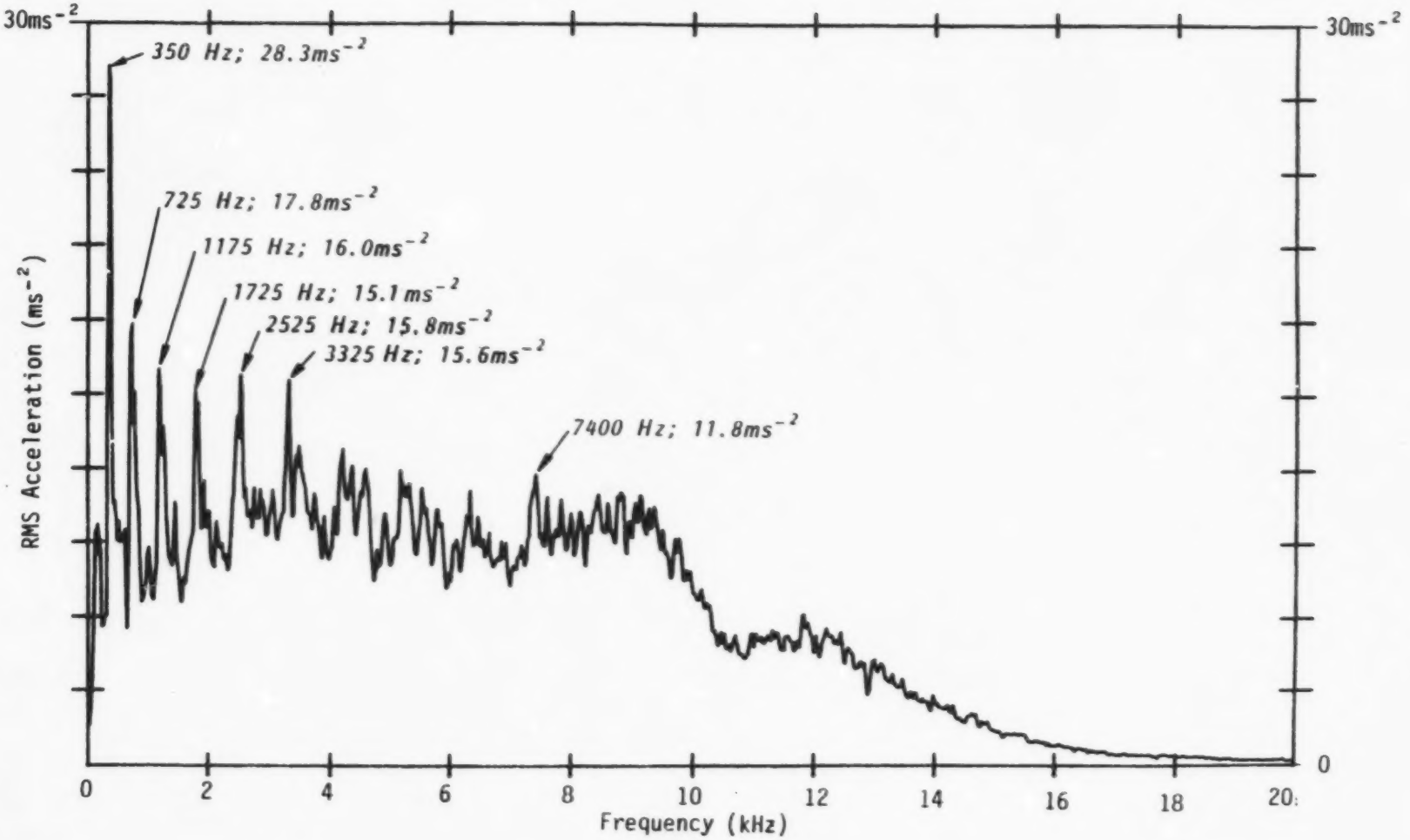


FIGURE 7 (c)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 4-PUMP OPERATION
DOWNSTREAM OF ORIFICE (POS. 10)

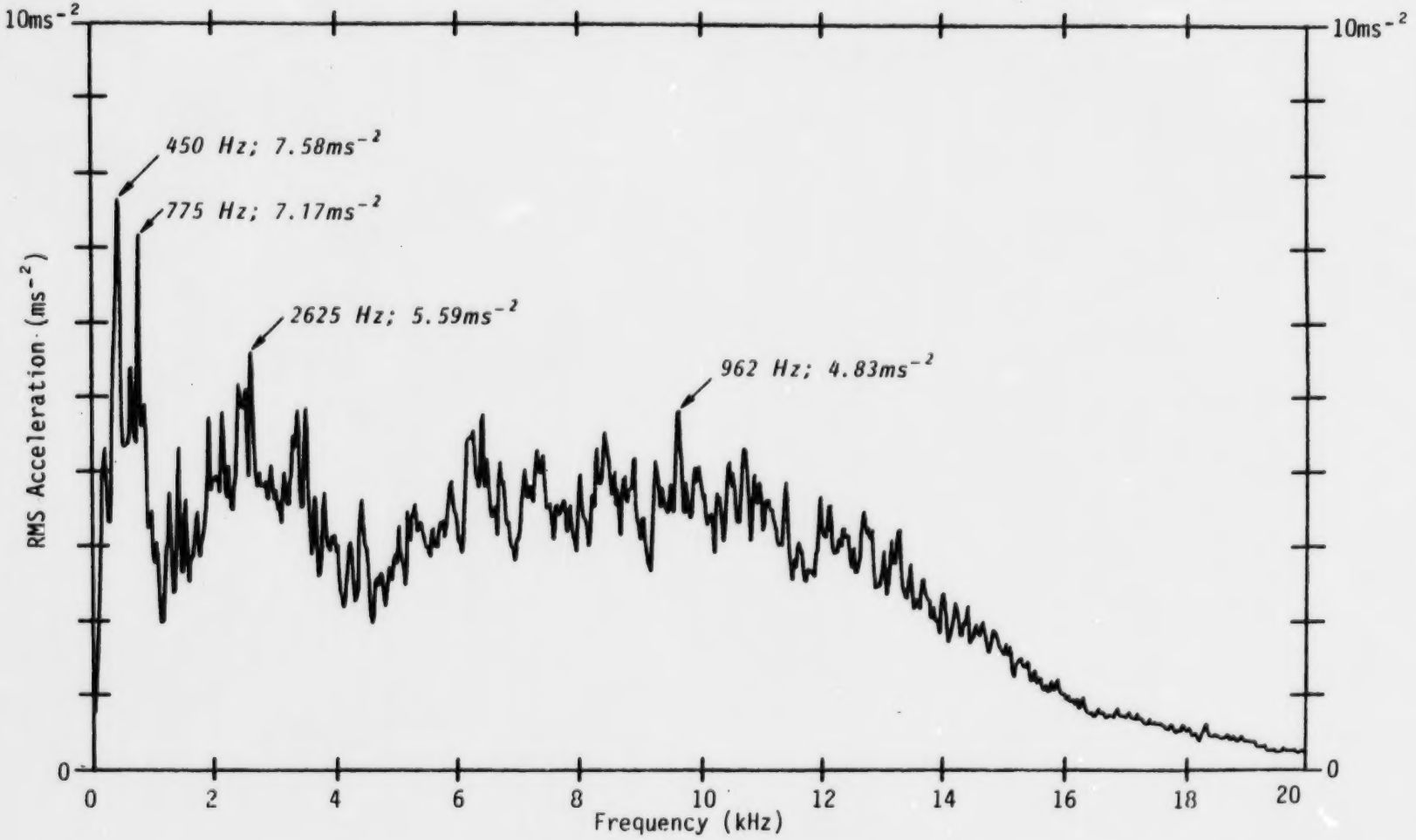


FIGURE 7 (d)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 4-PUMP OPERATION
1 FOOT UPSTREAM OF ORIFICE

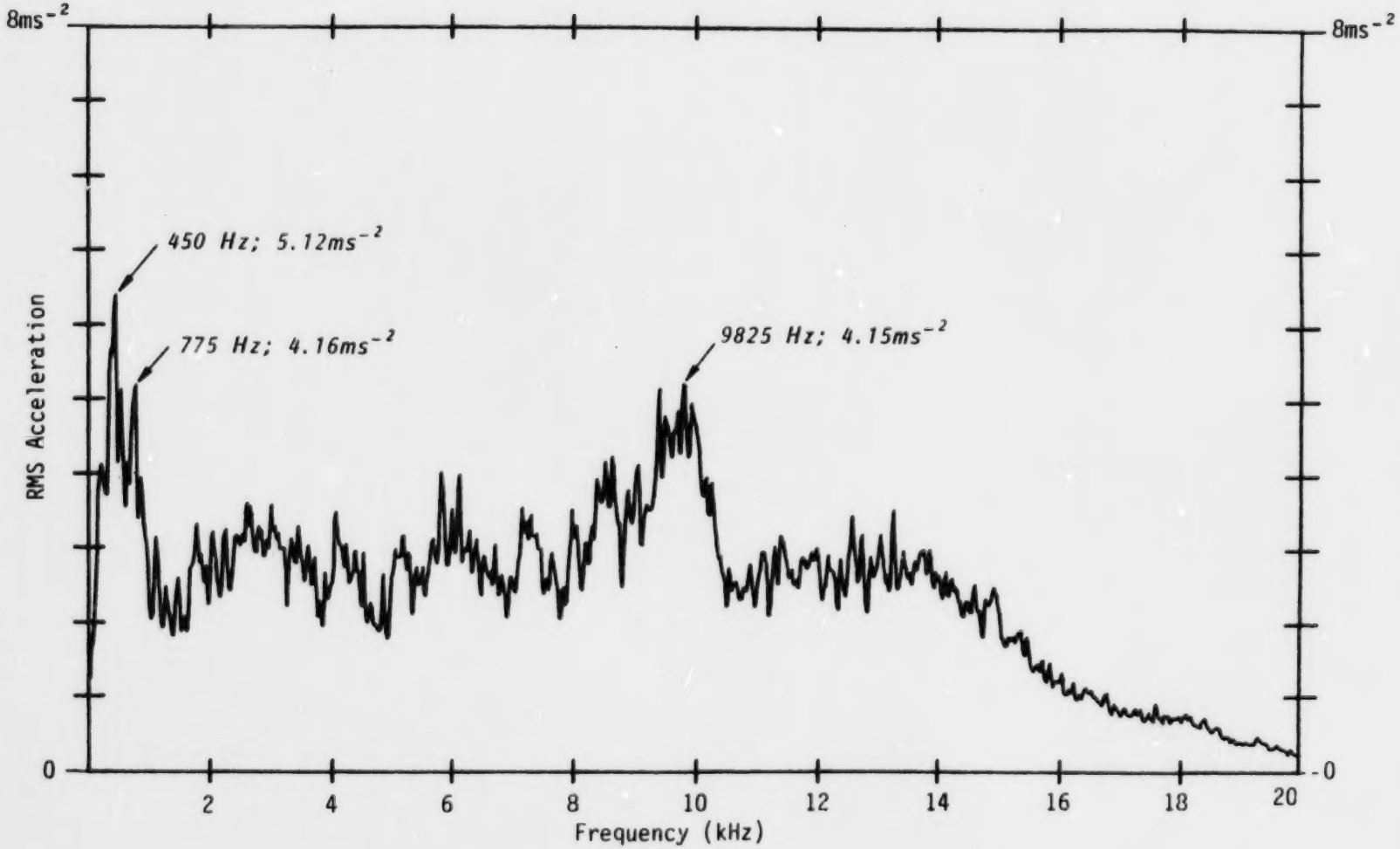


FIGURE 7 (e)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 3-PUMP OPERATION
1 FOOT UPSTREAM OF ORIFICE

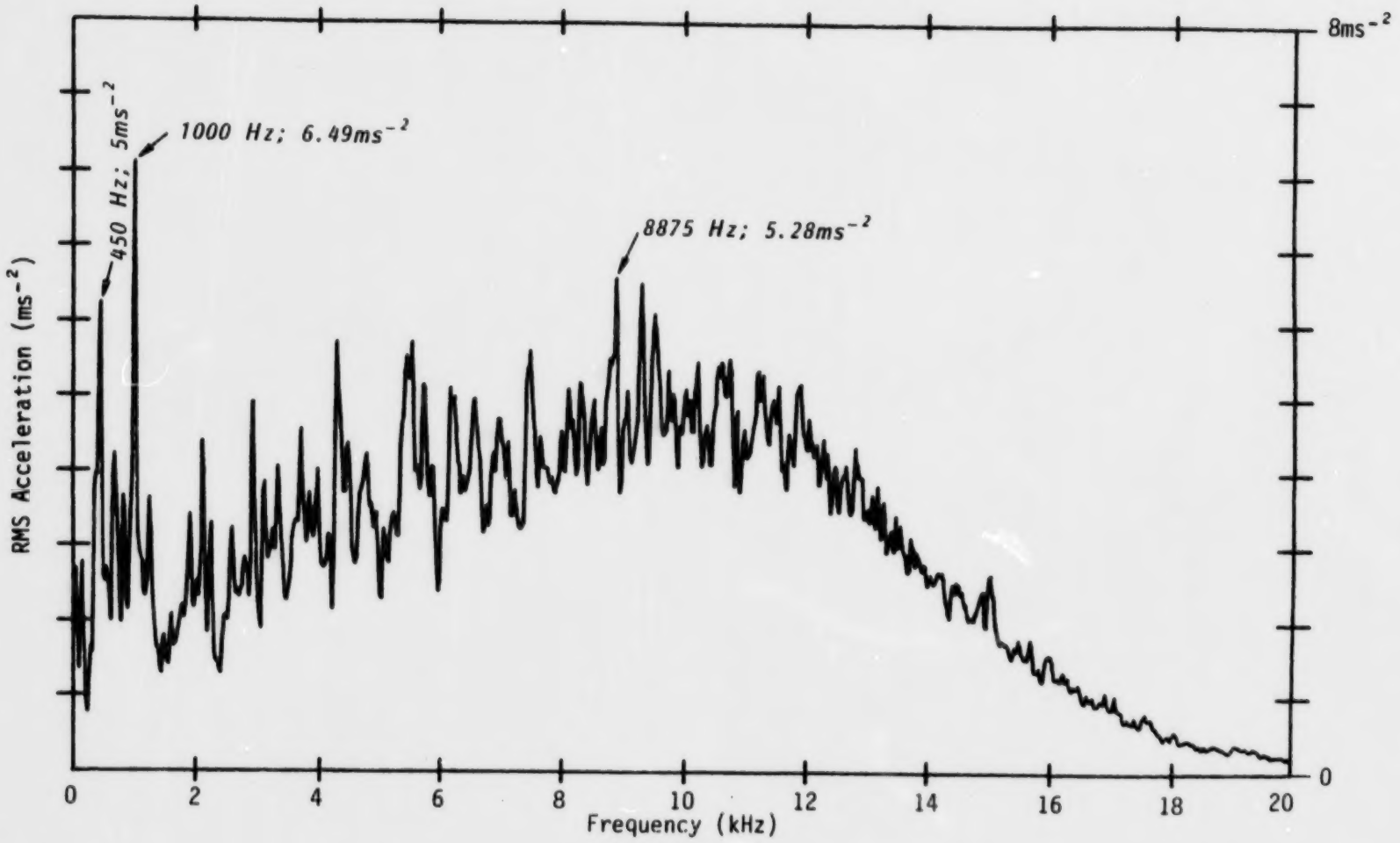


FIGURE 7 (f)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 3-PUMP OPERATION
WEST PIPE LOCATION

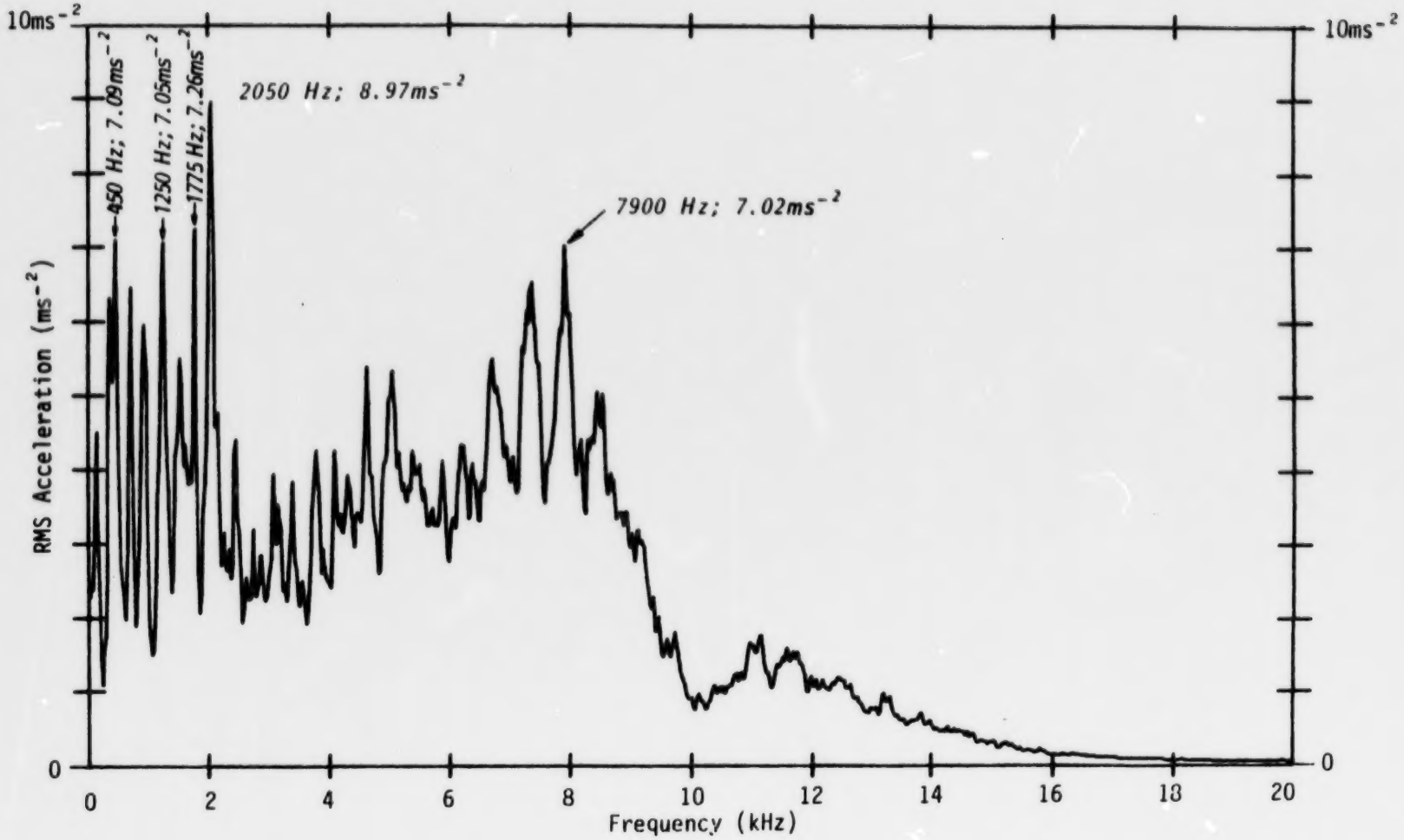


FIGURE 7 (g)

PNGS 'B' U6 MOD. PIPING VIBRO ACOUSTIC DATA 4-PUMP OPERATION EAST PIPE LOCATION

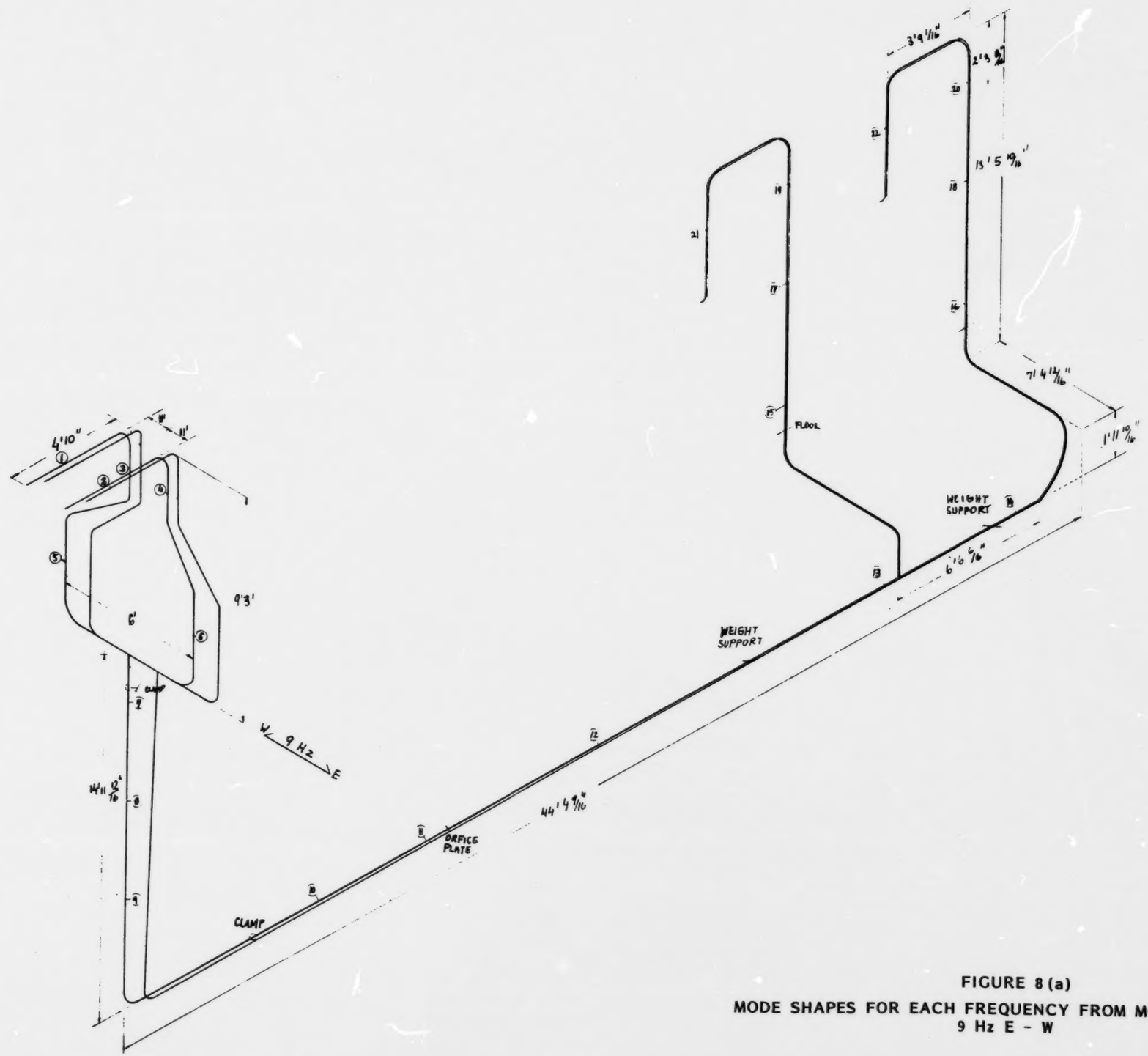


FIGURE 8 (a)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
9 Hz E - W

200776-RD

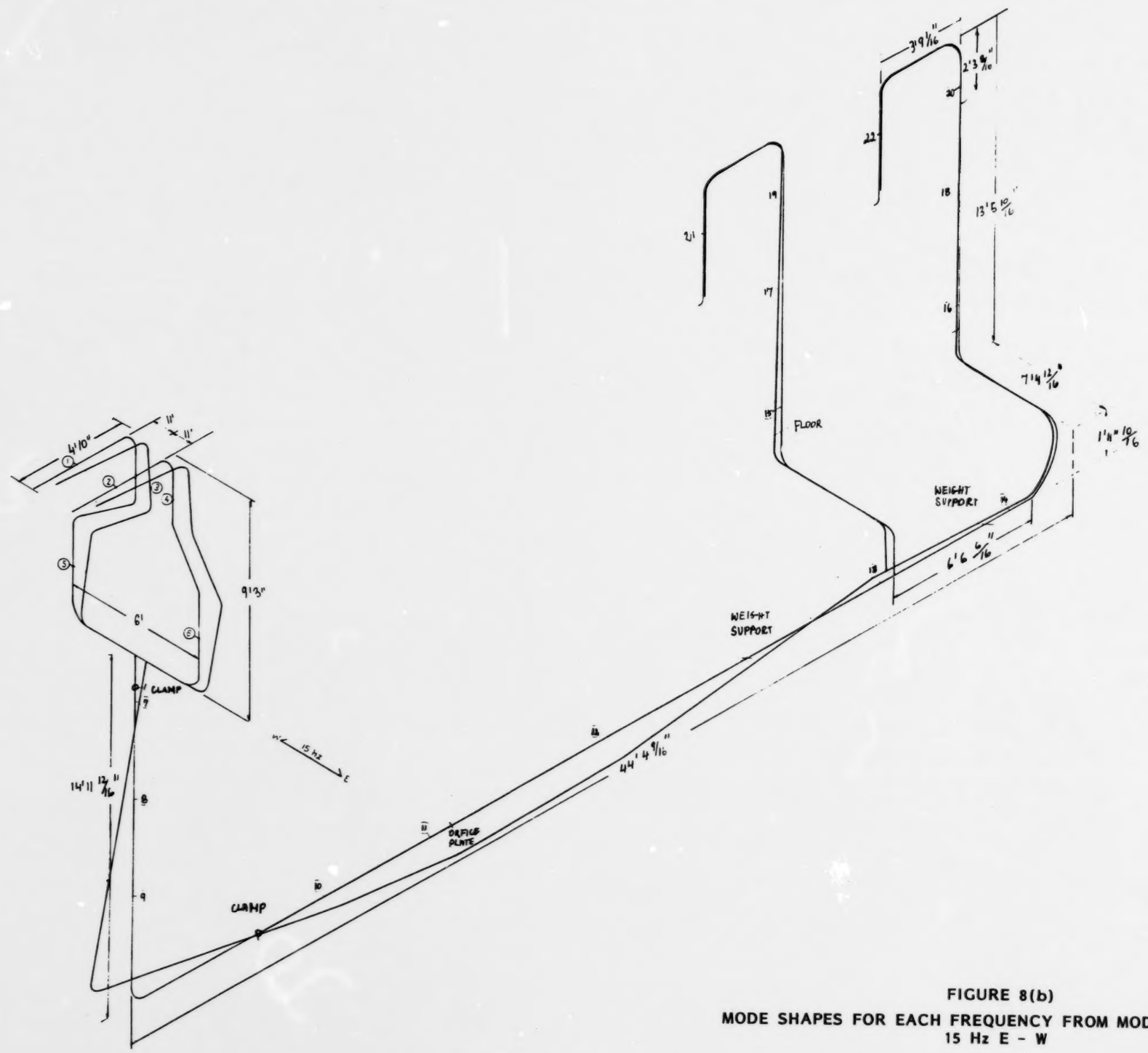


FIGURE 8(b)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
15 Hz E - W

200777-RD

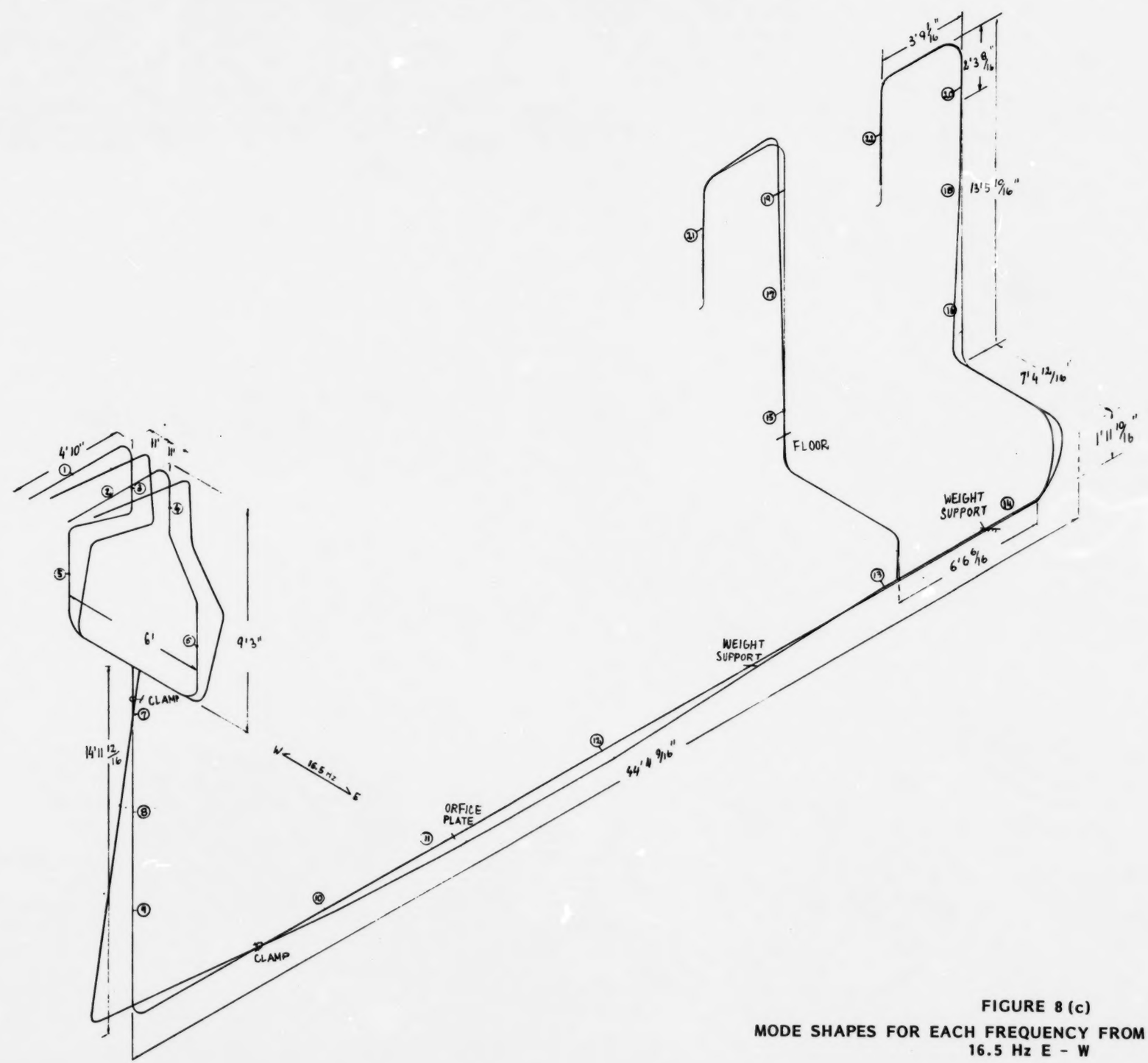


FIGURE 8 (c)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
16.5 Hz E - W

200778-RD

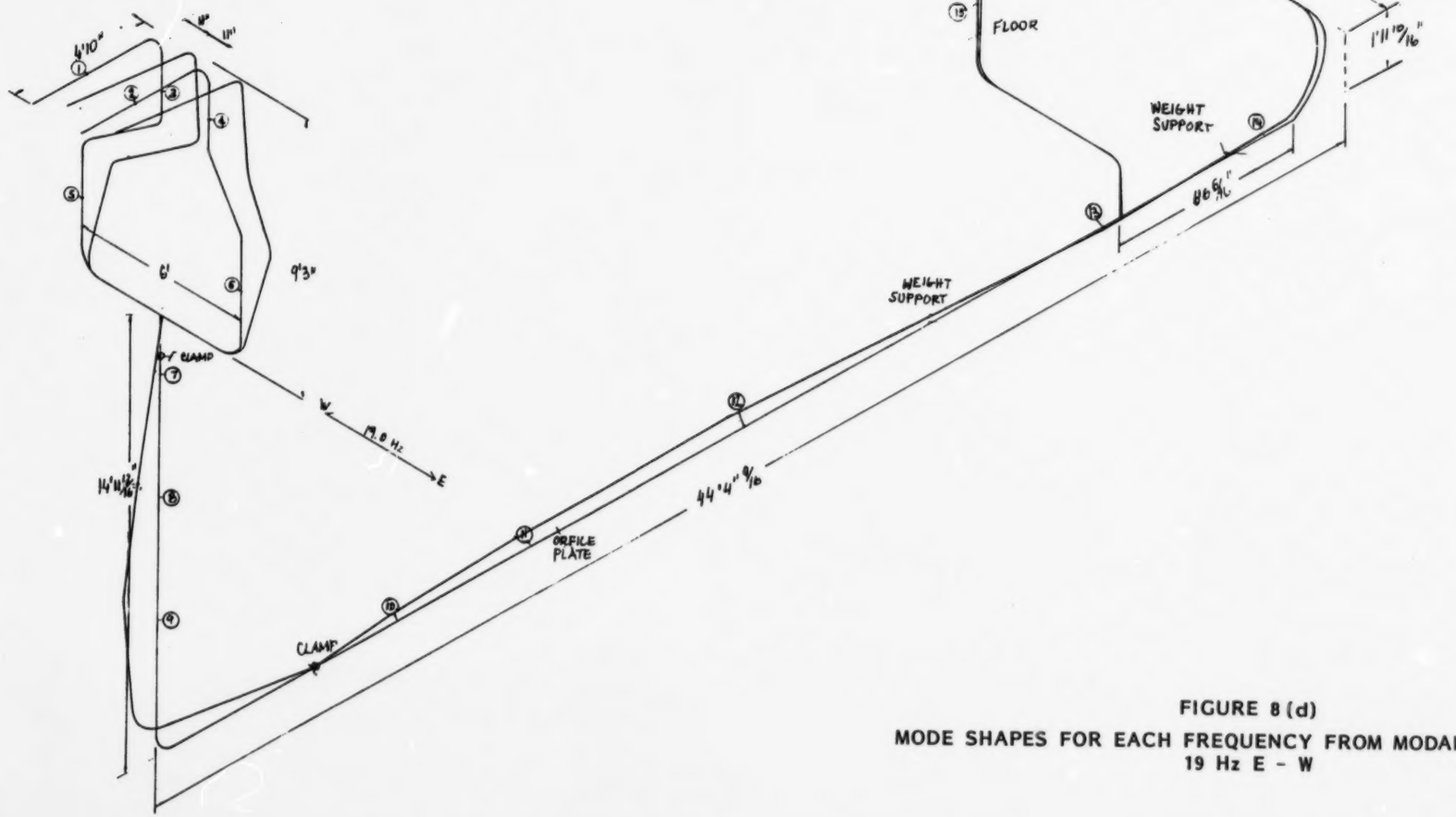


FIGURE 8 (d)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
19 Hz E - W

200779-RD

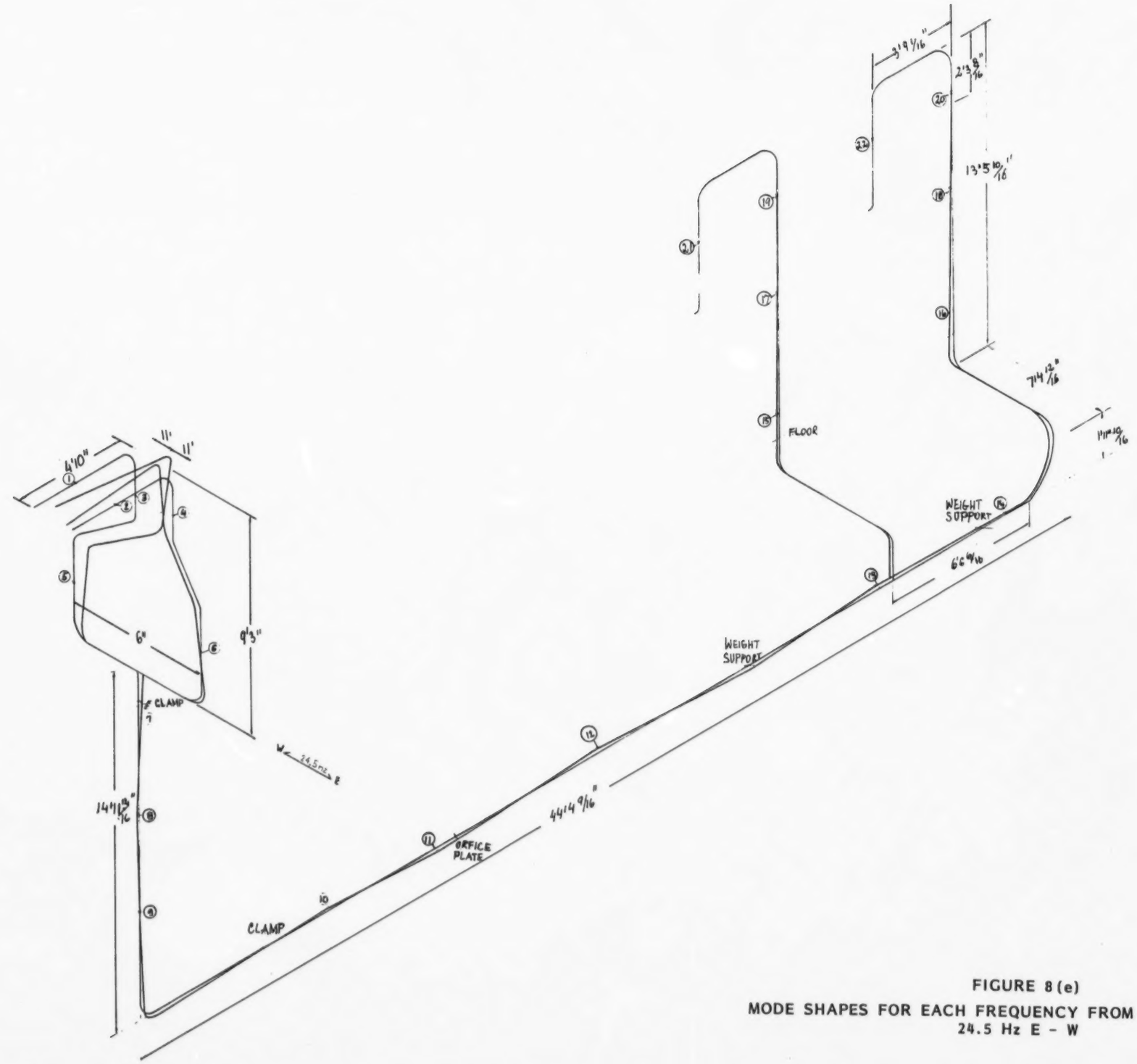


FIGURE 8 (e)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
24.5 Hz E - W

200780-RD

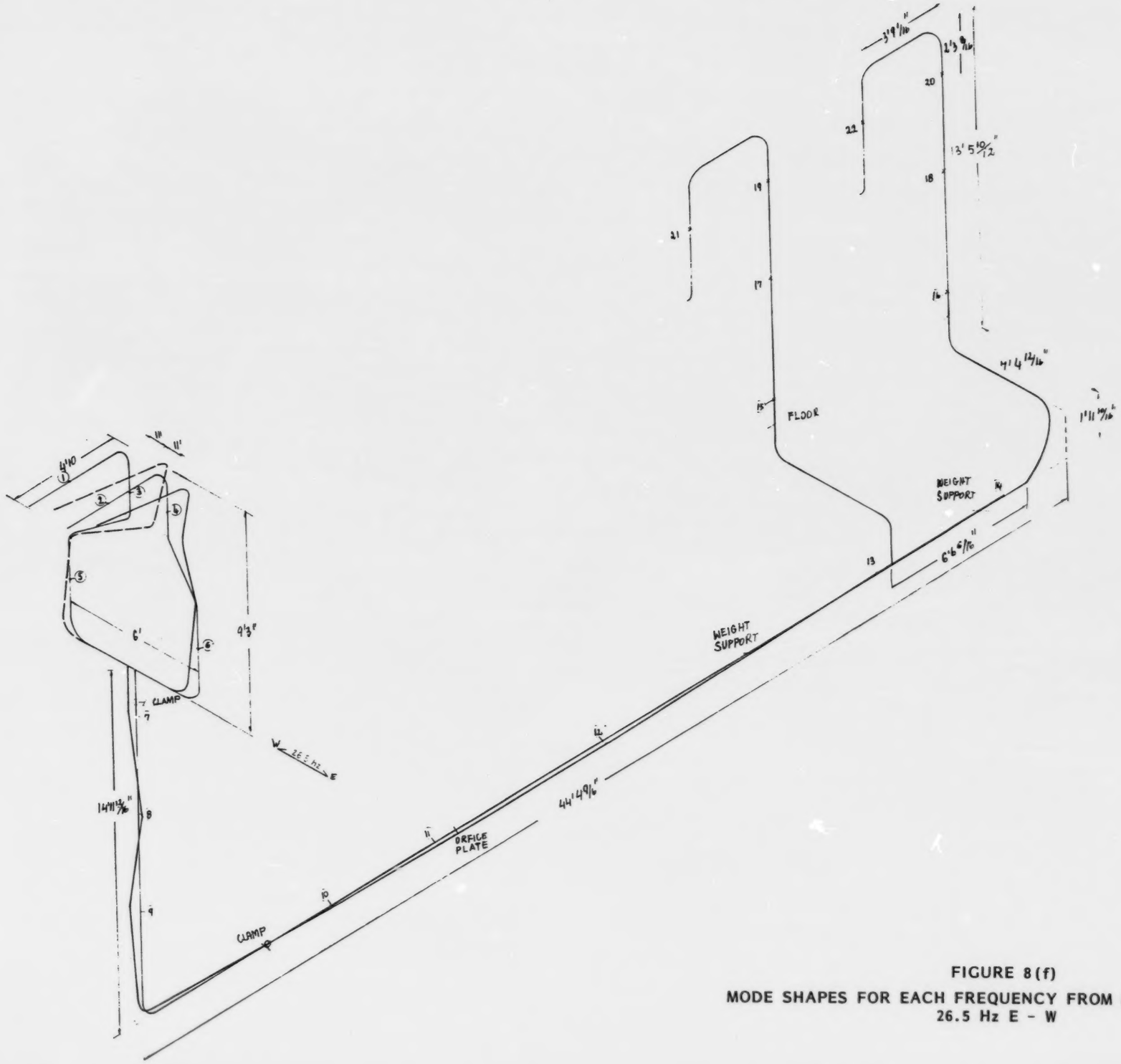


FIGURE 8(f)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
26.5 Hz E - W

200781-RD

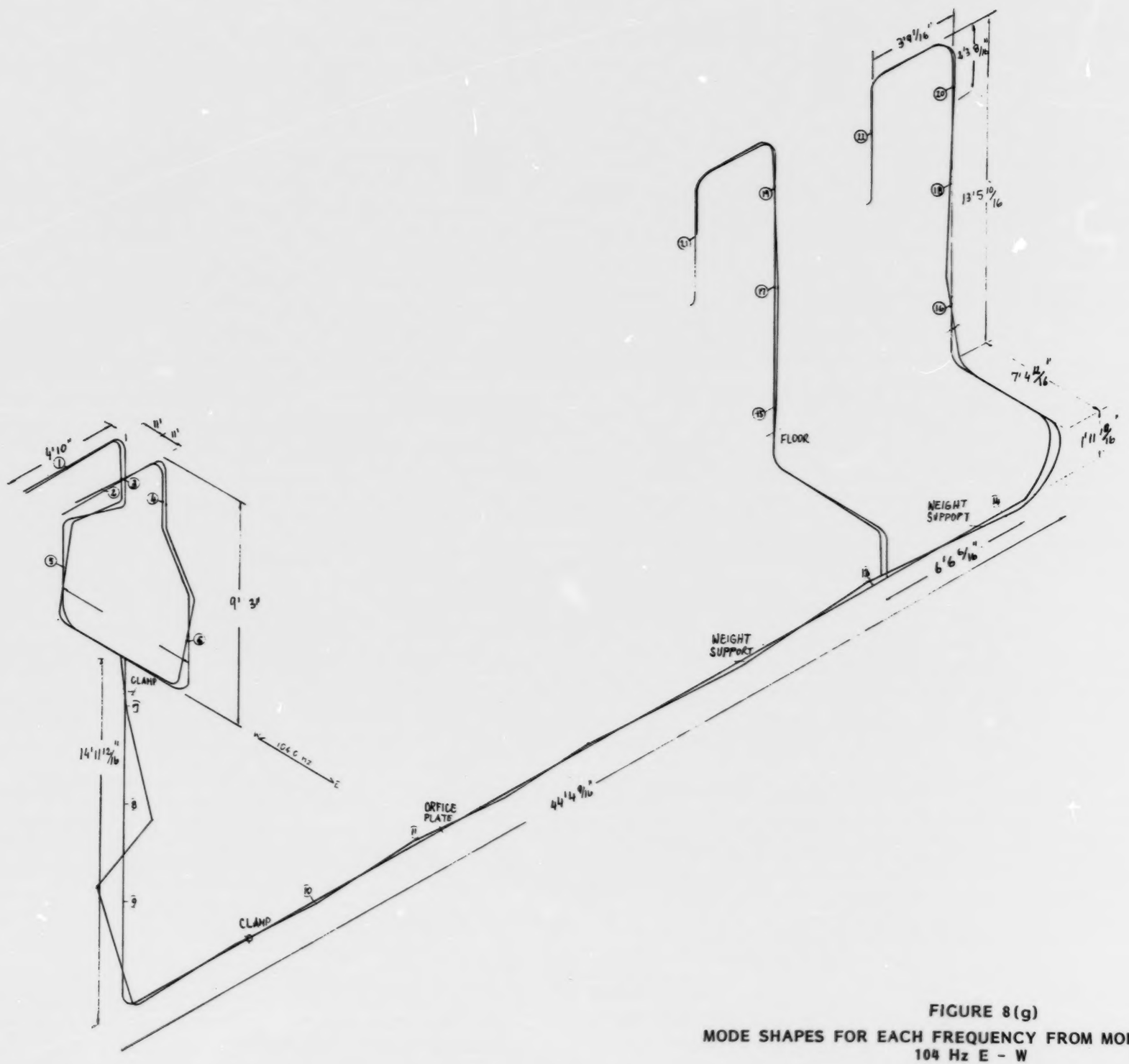


FIGURE 8(g)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
104 Hz E - W

200782-RD

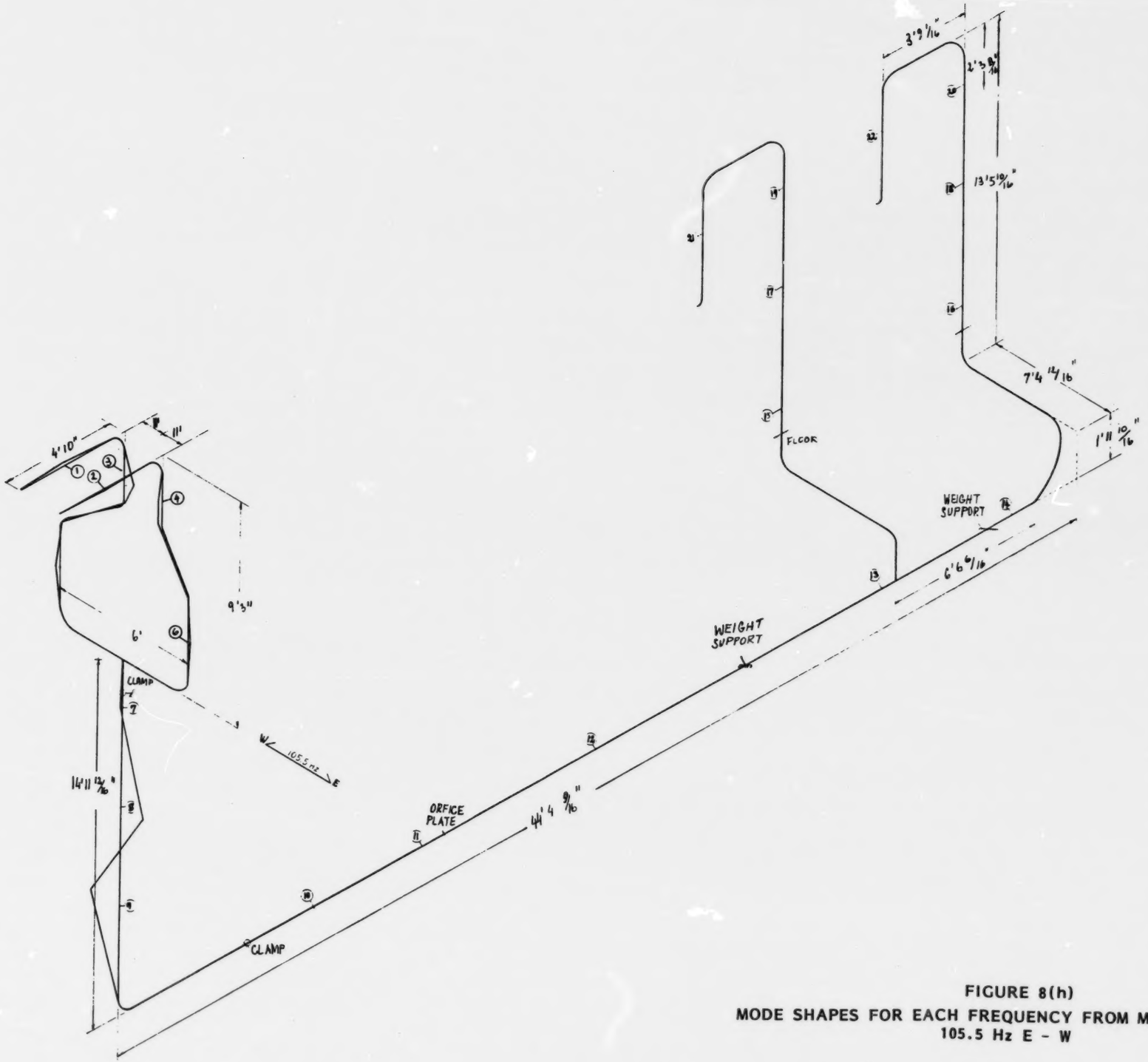


FIGURE 8(h)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
105.5 Hz E - W

200783-RD

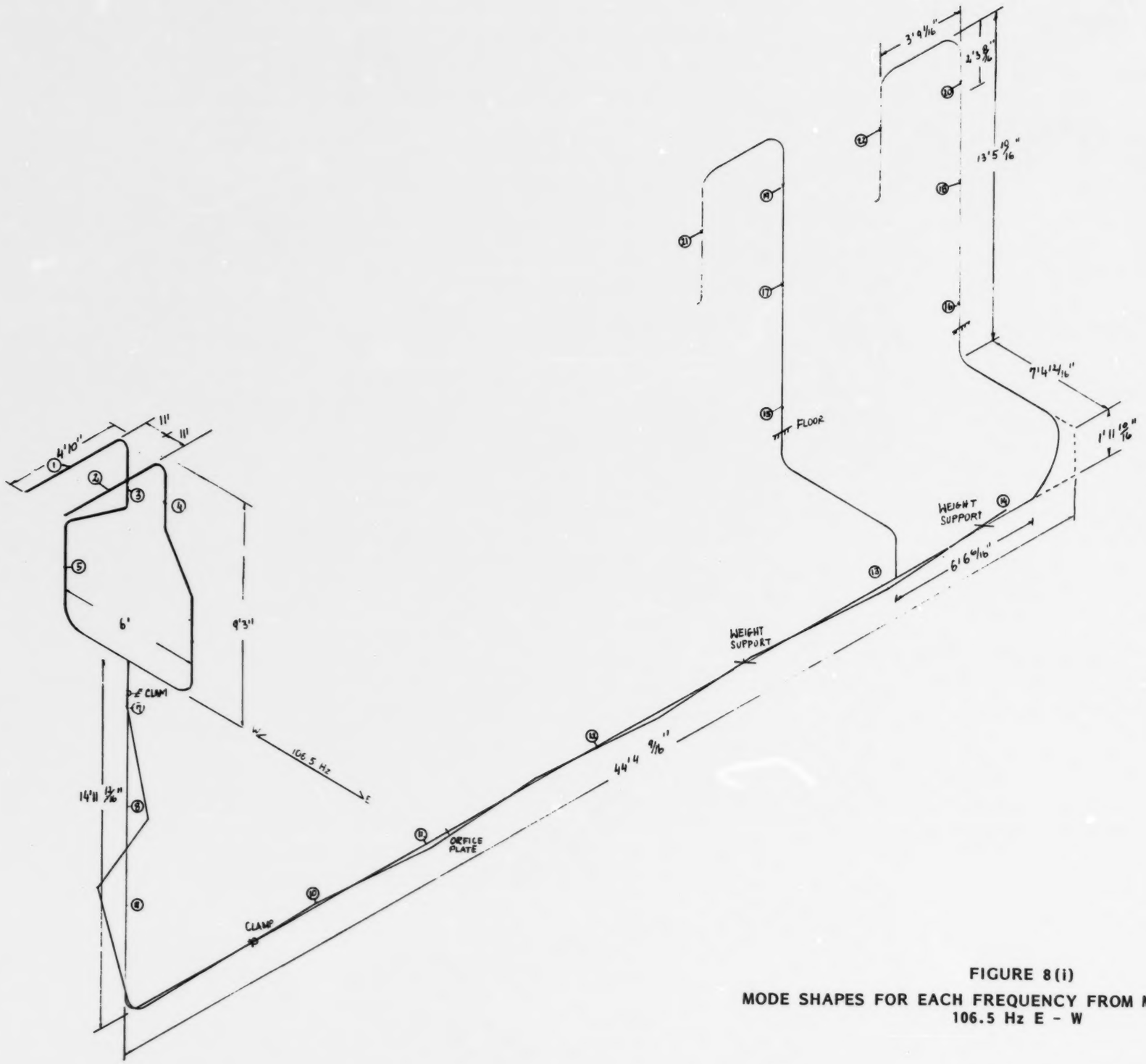


FIGURE 8(i)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
106.5 Hz E - W

200784-RD

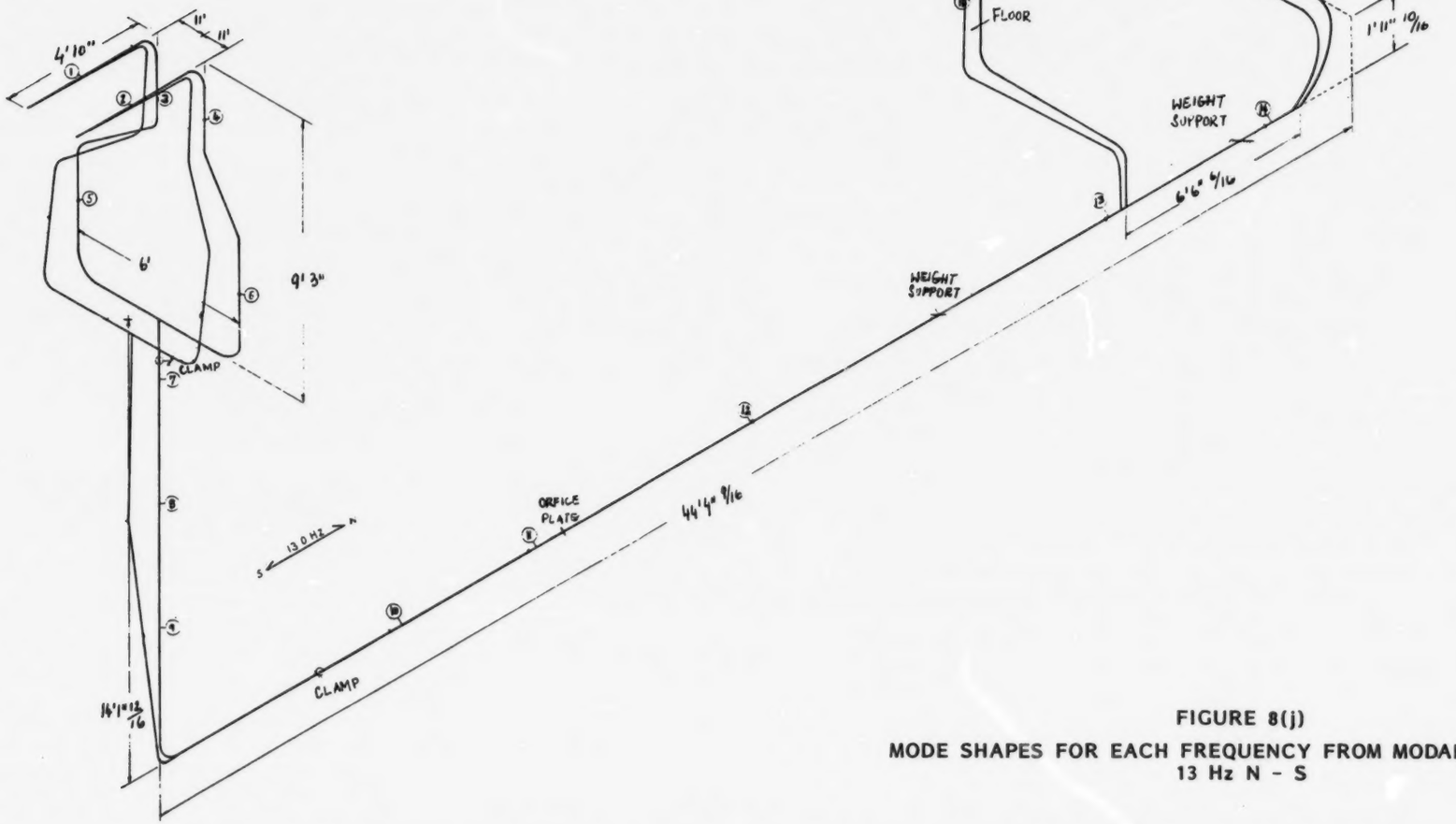


FIGURE 8(j)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
13 Hz N - S

200785-RD

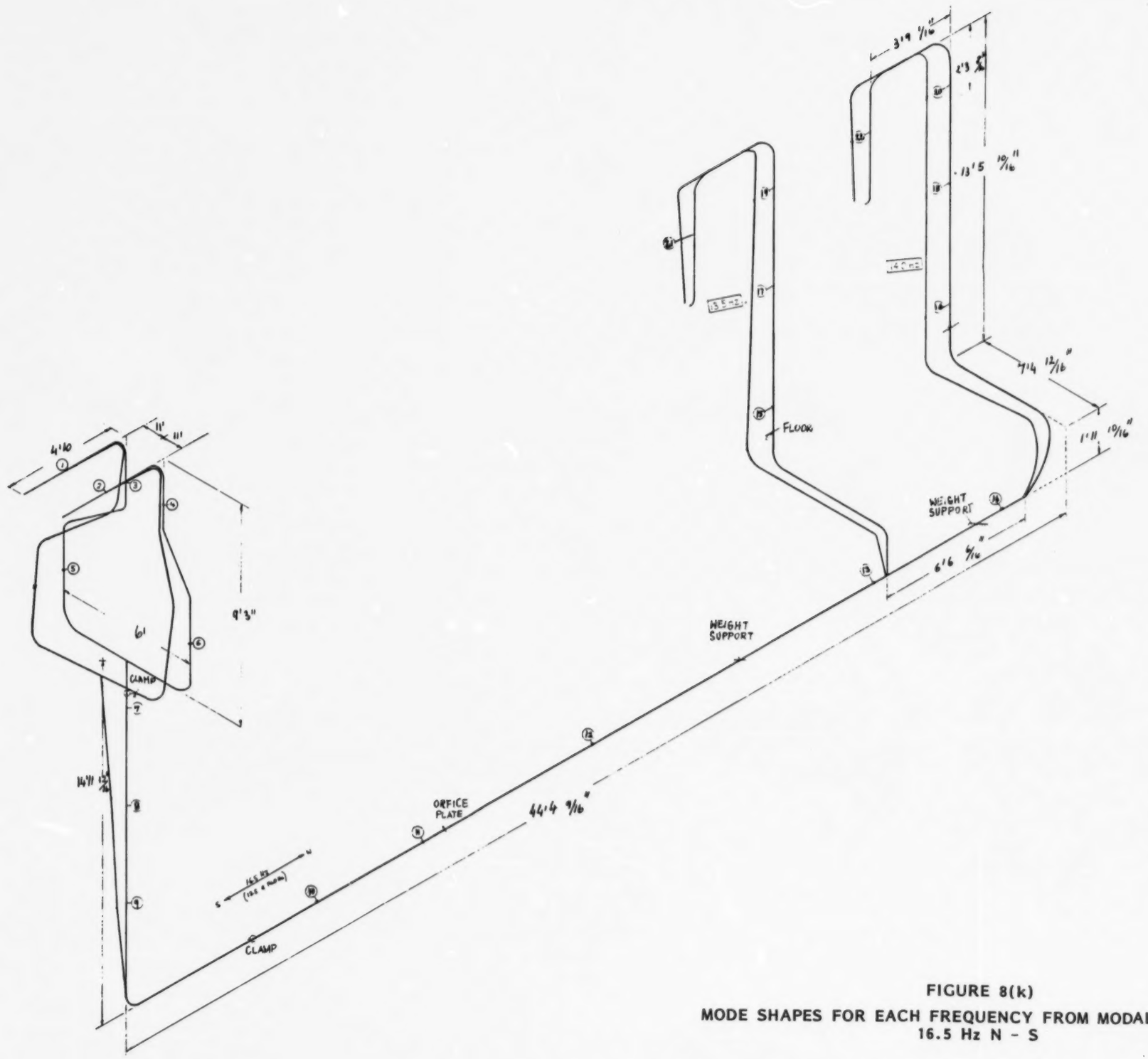


FIGURE 8(k)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
16.5 Hz N - S

200786-RD

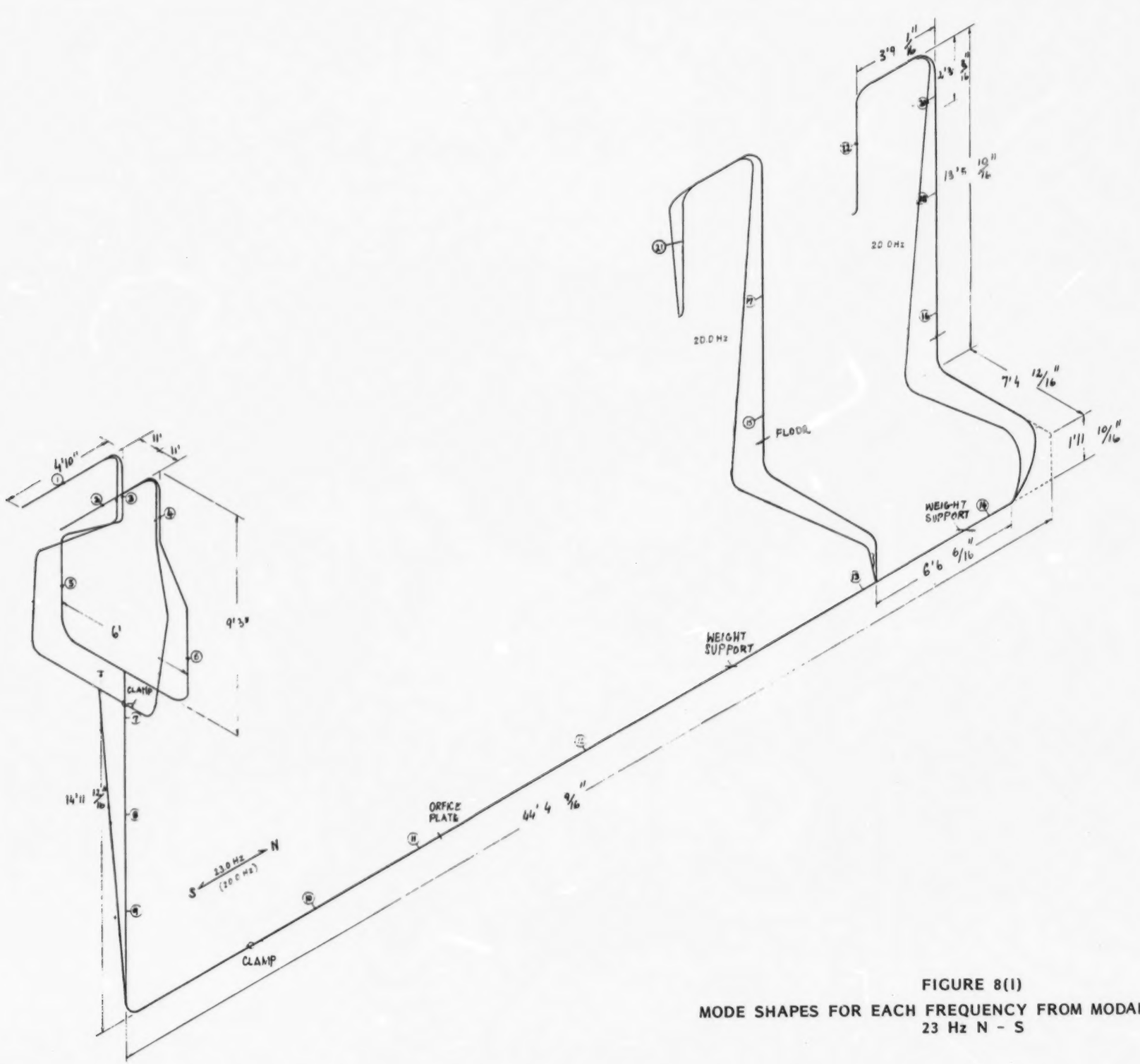


FIGURE 8(I)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
23 Hz N - S

200787-RD

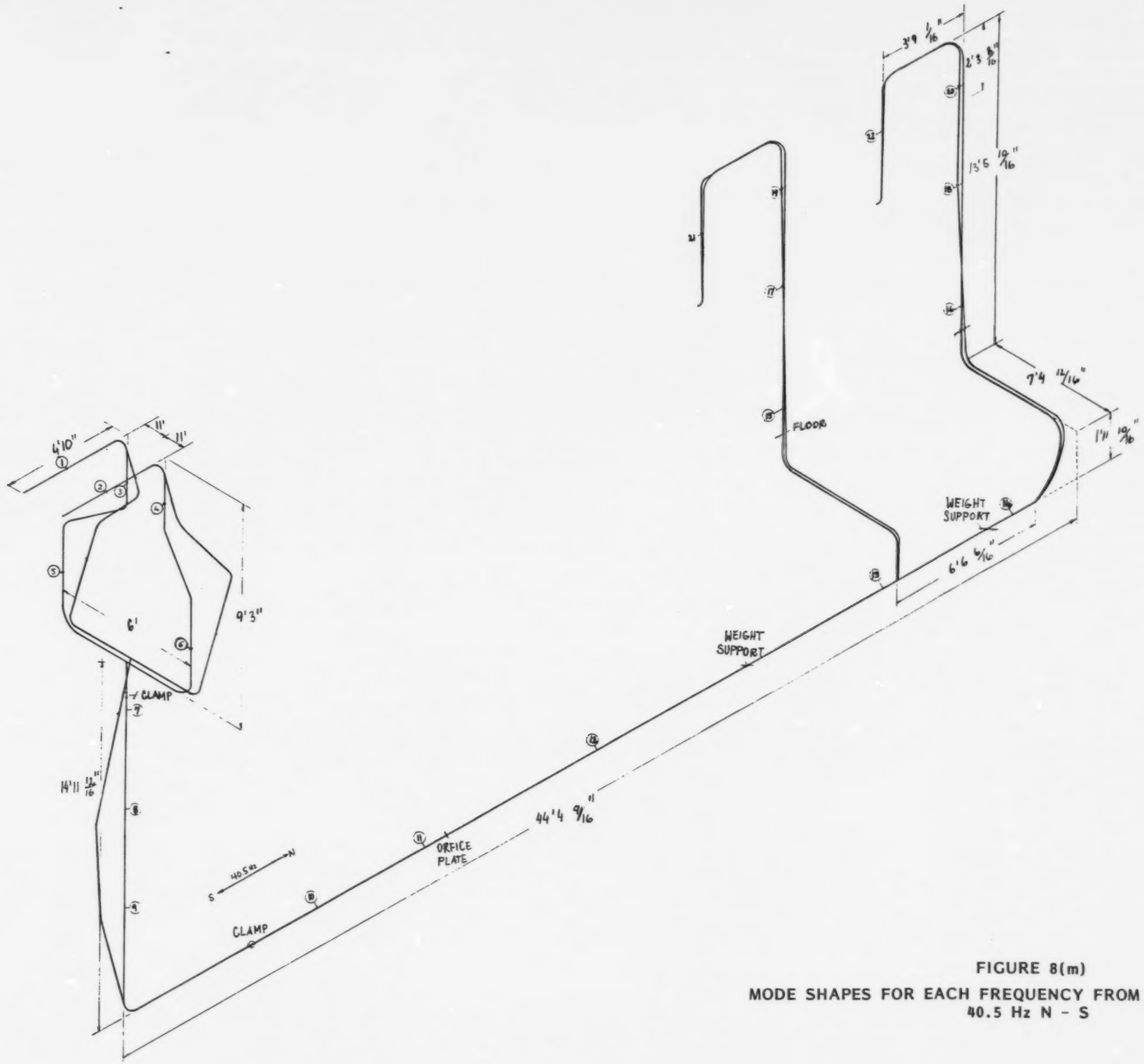


FIGURE 8(m)

MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
40.5 Hz N - S

200788-RD

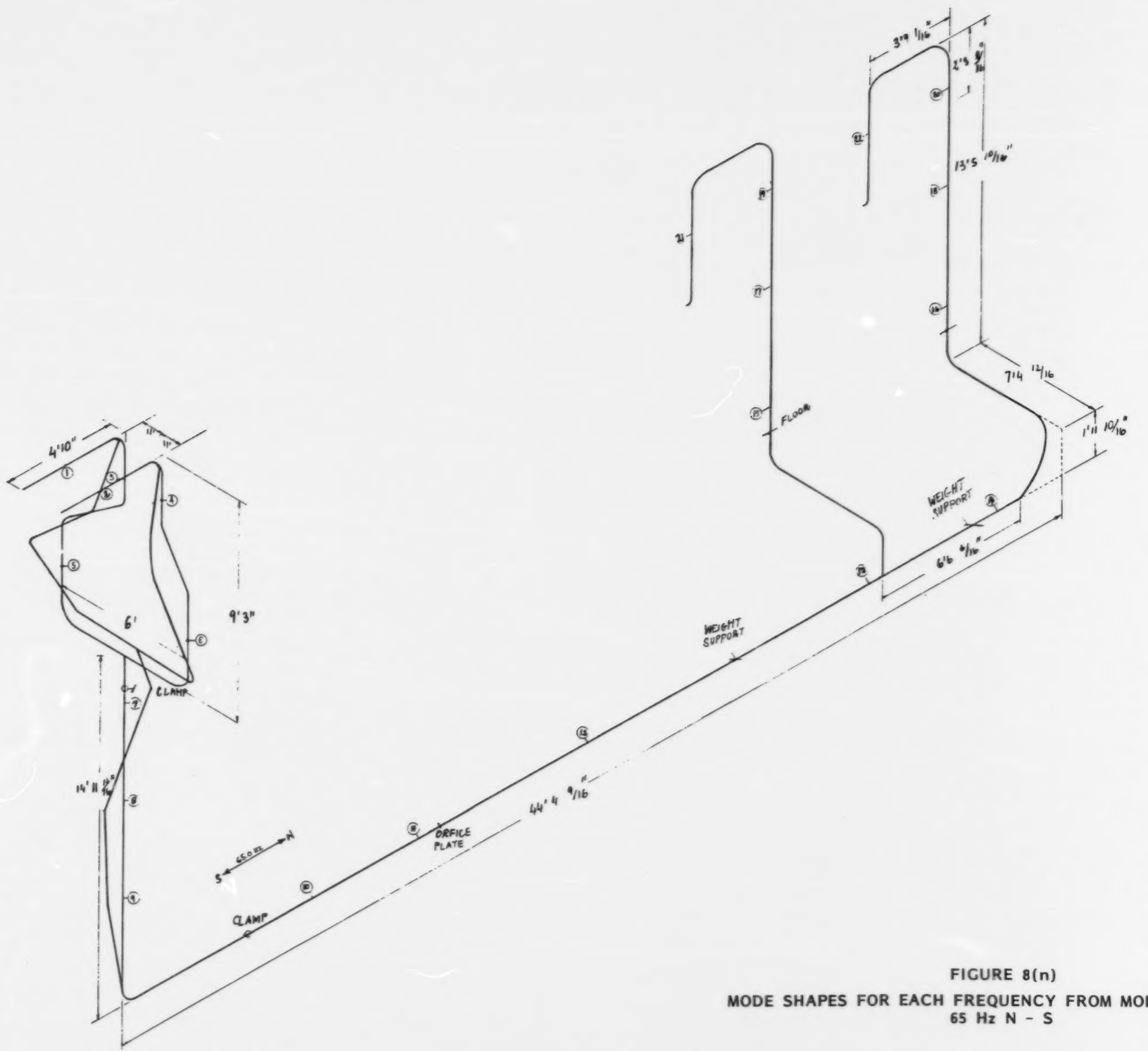


FIGURE 8(n)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
65 Hz N - S

200789-RD

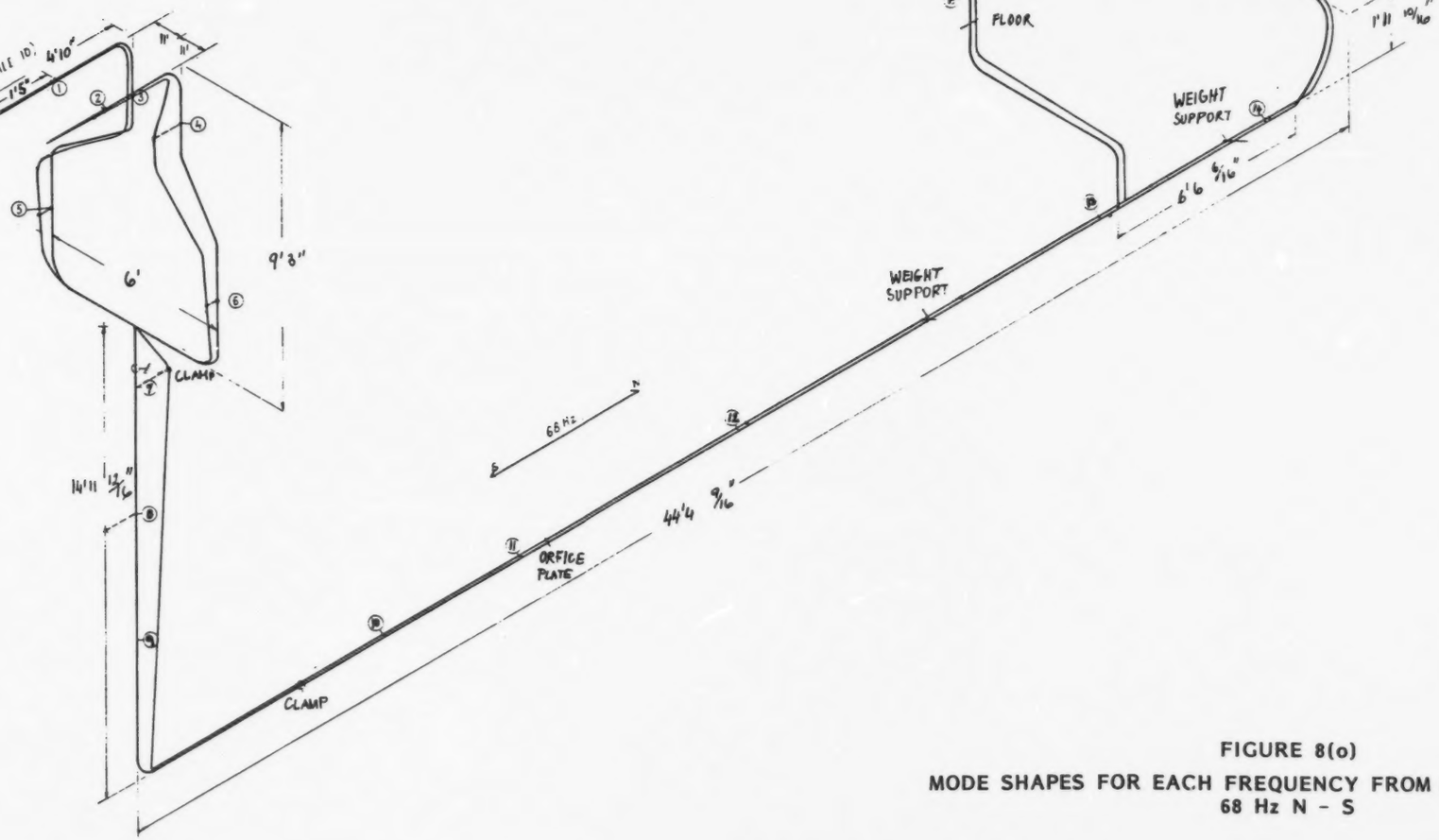


FIGURE 8(o)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
68 Hz N - S

200790-RD

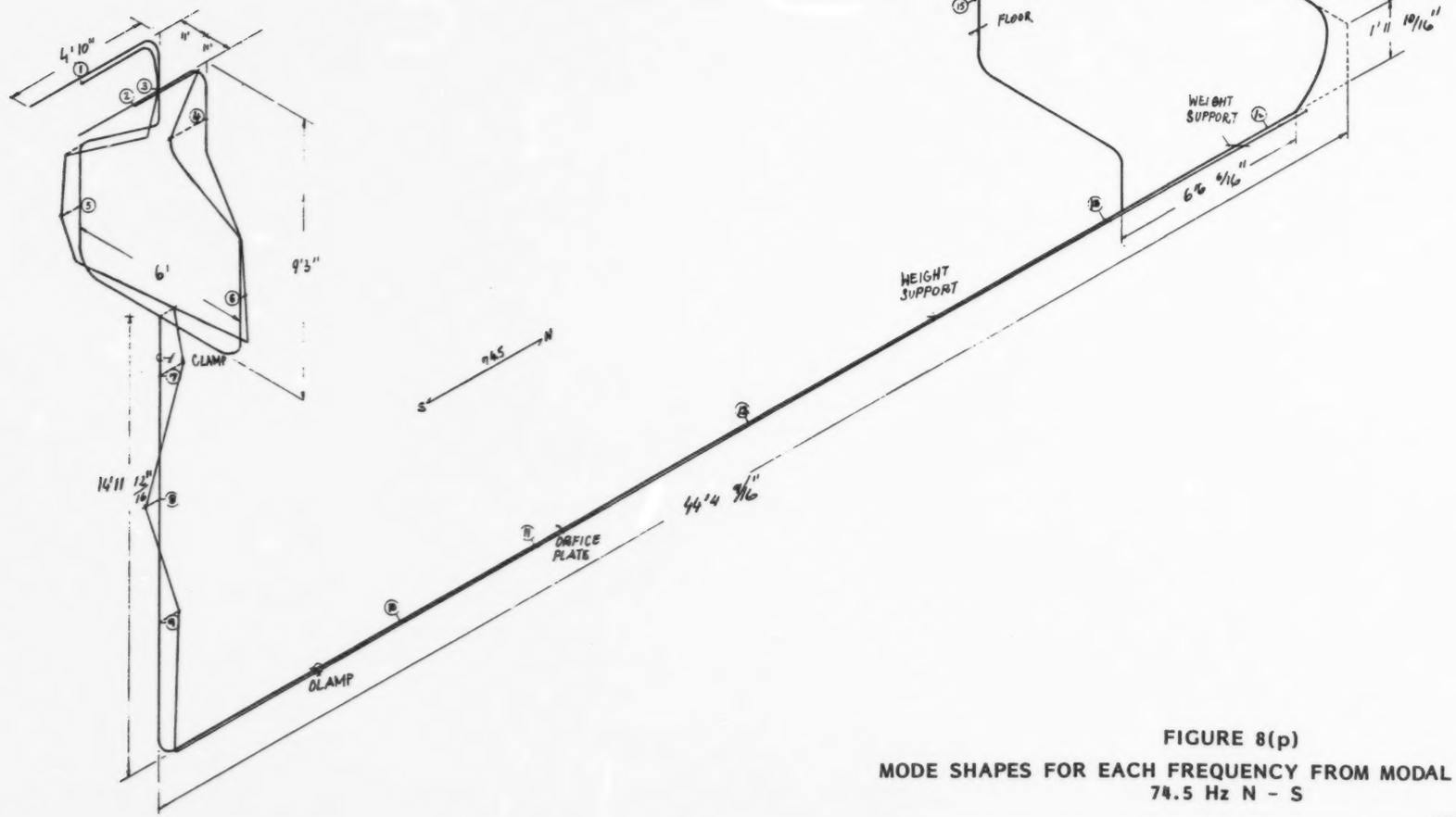


FIGURE 8(p)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
74.5 Hz N - S

200791-RD

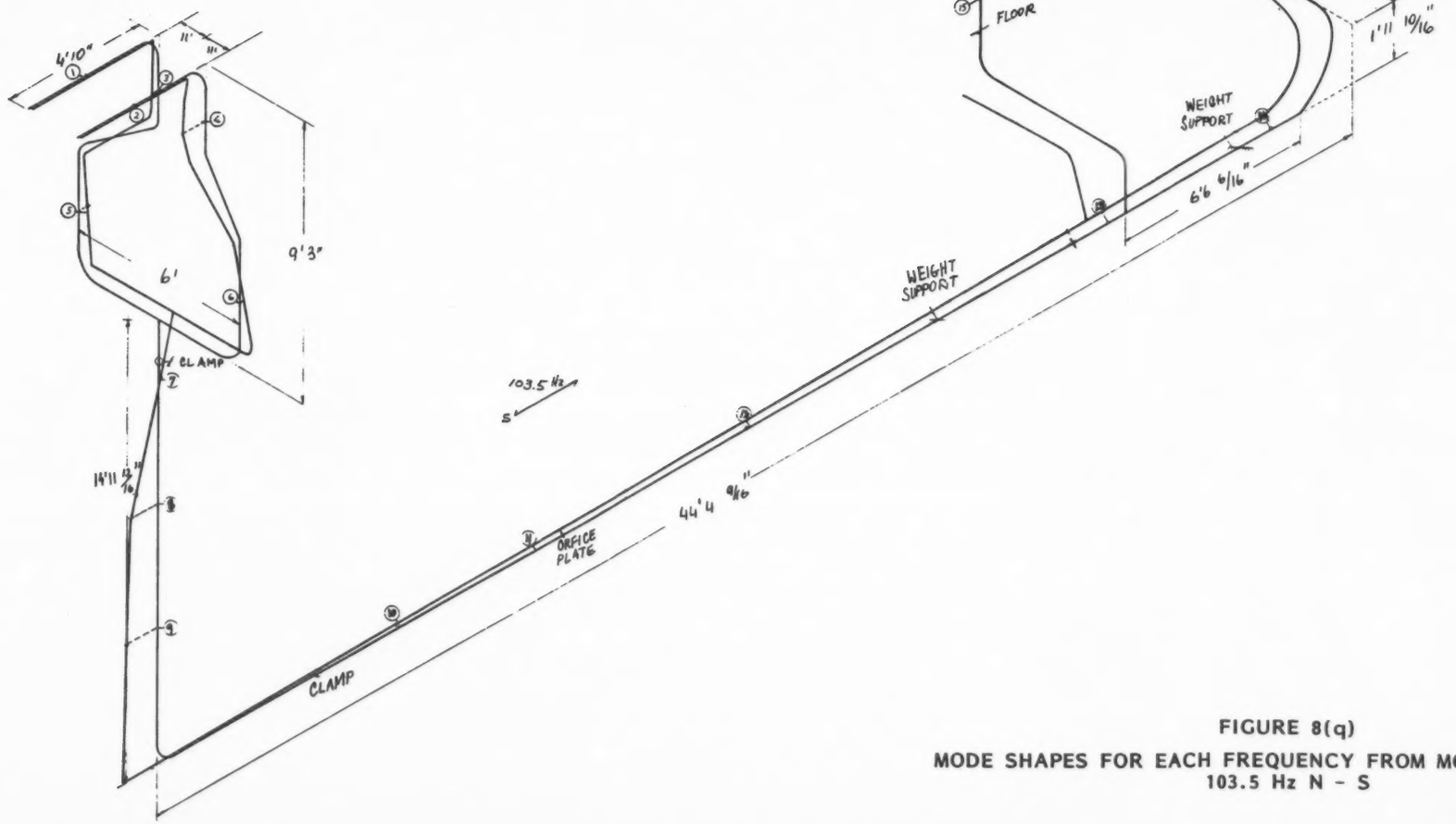


FIGURE 8(q)

MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
103.5 Hz N - S

200792-RD

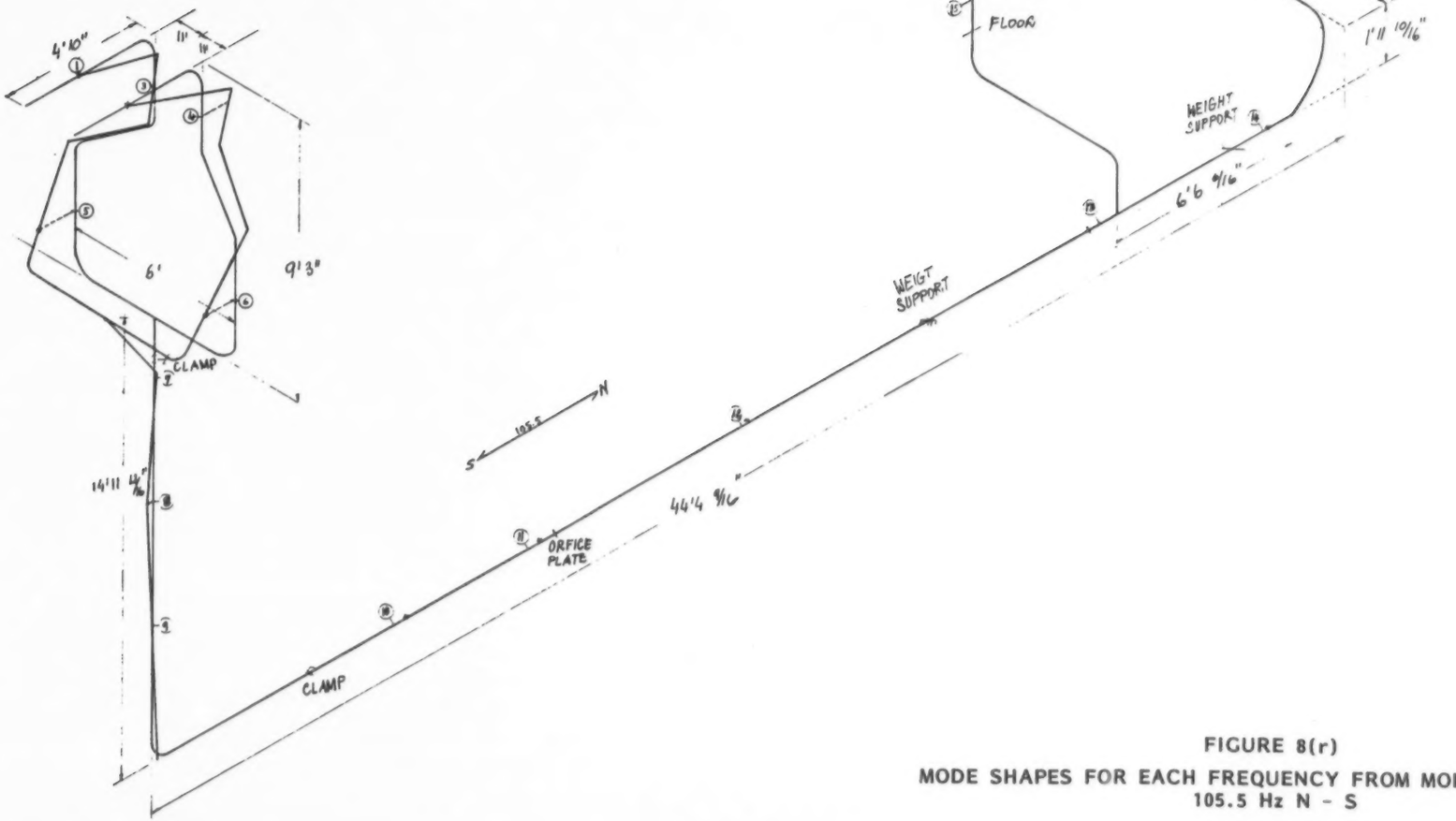


FIGURE 8(r)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
105.5 Hz N - S

200793-RD

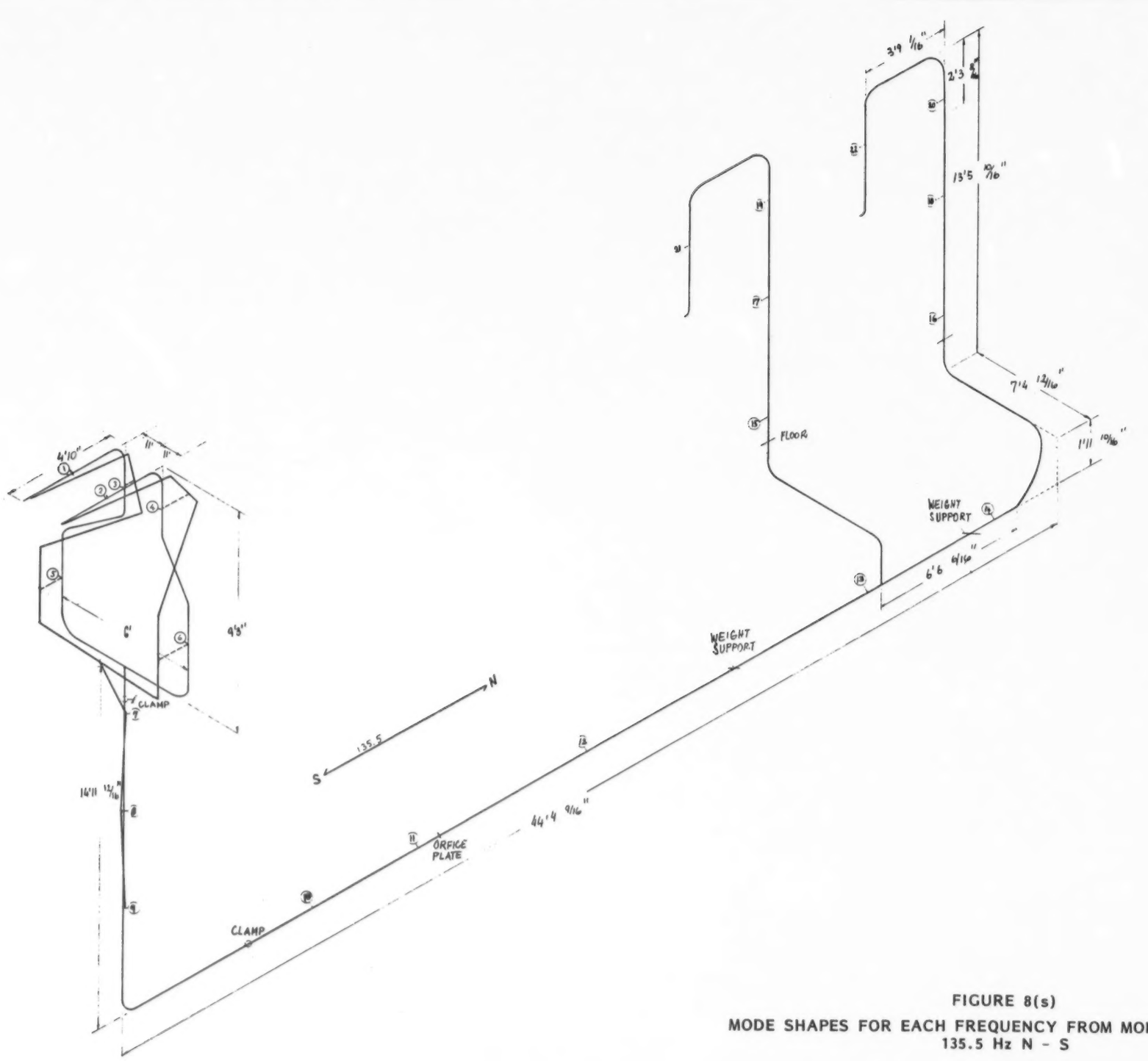


FIGURE 8(s)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
135.5 Hz N - S

200794-RD

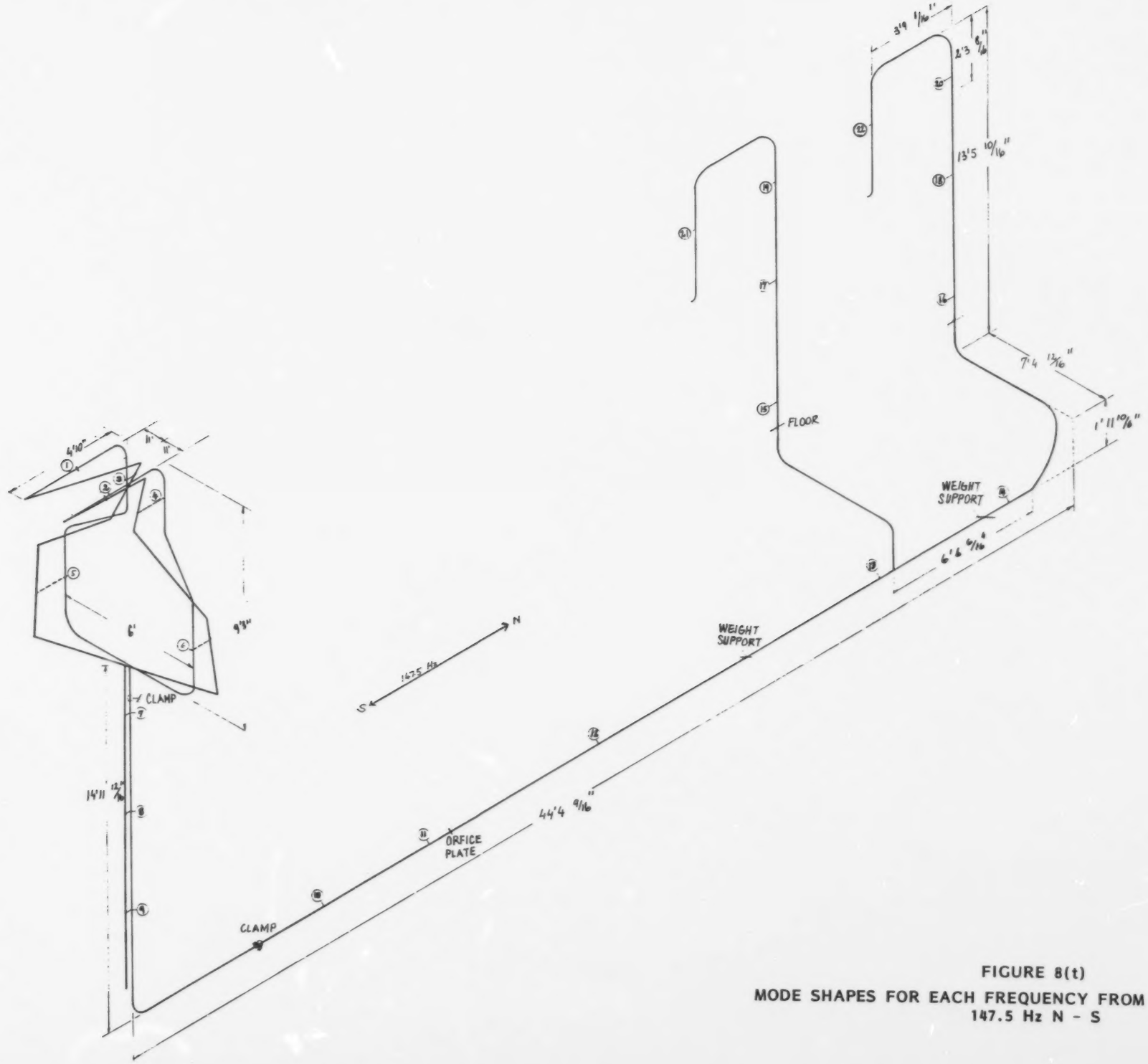


FIGURE 8(t)
MODE SHAPES FOR EACH FREQUENCY FROM MODAL TESTS
147.5 Hz N - S

200795-RD

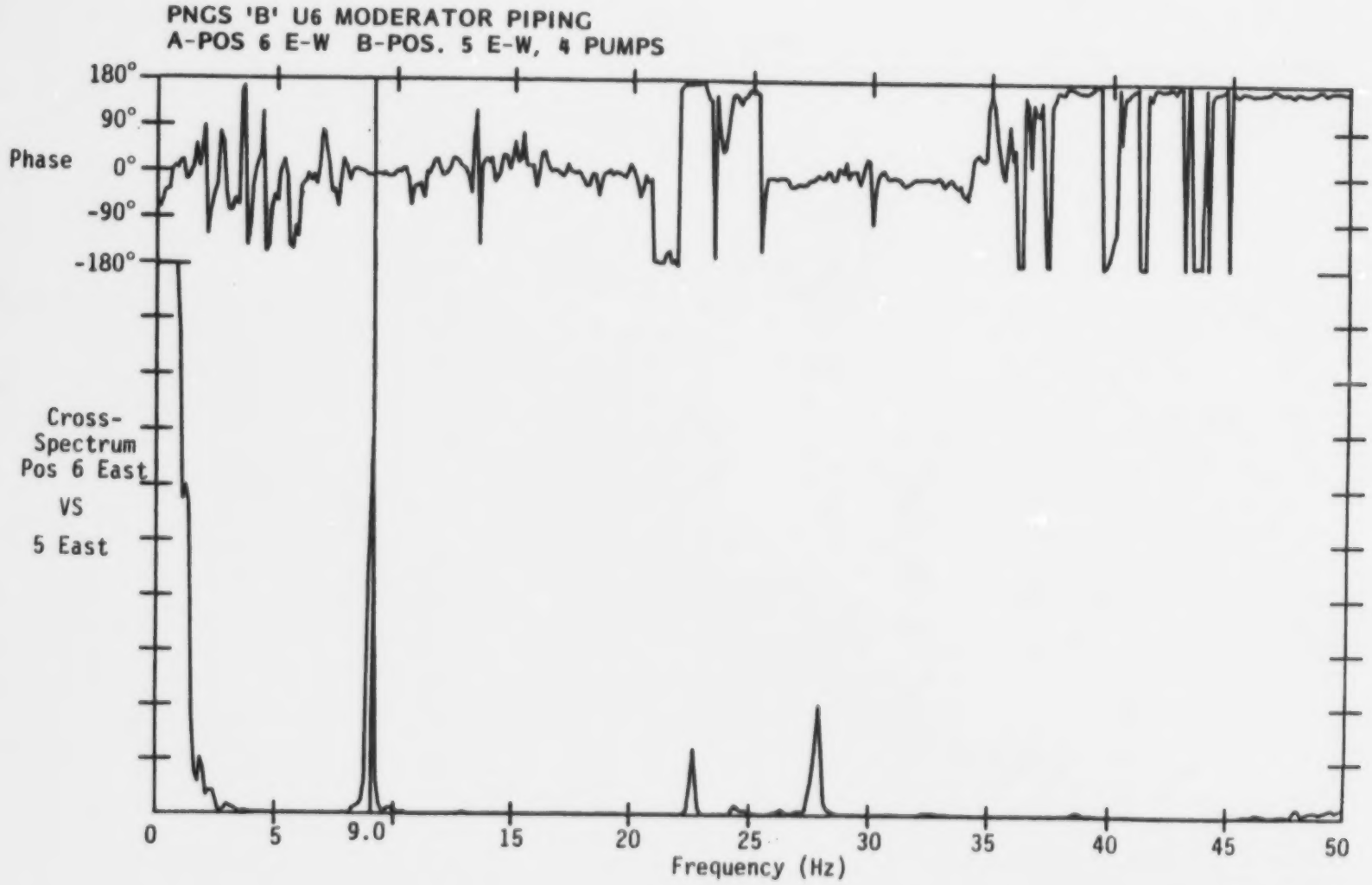


FIGURE 9

CROSS-SPECTRUM OF RUNNING DATA FOR POSITIONS 6E AND 5E, RECORDED SIMULTANEOUSLY WITH FOUR PUMPS IN OPERATION

APPENDIX A

PICKERING NGS 'B' MODERATOR PIPING VIBRATION DEVELOPMENT AND PROOF OF LONG-TERM SOLUTION PROPOSED MOCK-UP TEST LOOP/A1/

1. Background

In mid-December 1986, Nuclear Systems Department asked us to investigate feasibility, cost, and schedule for a test program. The scope was limited to performance testing of a multi-hole "energy-Dissipator" proposed to replace the existing single orifice and thereby reduce the extent and effects of cavitation.

Our first consideration was to attempt to use the existing full-scale PHT pump-test loop. This proved to be not feasible due to gross mismatch of the available and required process conditions, NPSH considerations, and controllability.

The next consideration was to assemble a special-built test loop around a suitable pumping machine. This approach is feasible and technically sound but would have required two to three months to assemble the loop. Thus it could not have contributed to short-term decisions regarding immediate modifications. Thus we were not asked to proceed with procurement and construction.

2. Suggested Expansion of Scope

A mock-up test loop would be very helpful toward achieving a satisfactory long-term solution to the moderator piping vibration. As discussed with you and your staff, the scope could include:

- develop a thorough diagnosis and understanding of the cause of the vibration
- extend the investigation to cover the piping right up the inlets of the calandria
- develop and prove-out corrective modifications, including consideration of alternatives.

A mock-up test loop to address these important points could be assembled within a time frame of a few months.

3. Proposed Test Loop

One key to the feasibility and schedule is the availability of a suitable pumping machine. We have established that one Darlington Moderator Pump would be ideally suited for the purpose. Darlington project personnel have informally indicated that machine deliveries and project schedule could make a pump available for the required time. It appears that given sufficient 'corporate' priority, approval for use of a Darlington machine could be obtained.

The balance of the test loop would consist of simulation of the circuit layout to the extent required, and the provision of power, necessary auxiliaries, control and instrumentation. The entire undertaking is within the capabilities of our NPCTF staff; construction time could be minimized by use of external manpower. Additional specialized instrumentation (eg, pressure-pulsation transducers, vibration pick-ups, cavitation detectors, etc) could be added as required to meet the needs of the investigative/corrective program. The loop could be ready in approximately three months at a cost of $275,000. Allowing about $125,000 for a thorough test program would bring the total cost to $400,000.

Reference A1: Memo from R.T. Hartlen, "Pickering NGS 'B" Moderator Piping Vibration. Development and Proof of Long Term Solution; Proposed mock-up Test Loop", file 822.92(P), January 6, 1987.

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